Gumm and Lansche.

Further Development And Testing Of A Direct Reading Dynamometer.

FURTHER DEVELOPMENT AND TESTING

OF A

DIRECT READING DYNAMOMETER

BY

LESLIE MONROE GUMM

AND

ORAL ALBERT LANSCHE

THESIS

FOR THE

DEGREE OF BACHELOR OF SCIENCE

IN

ELECTRICAL ENGINEERING

COLLEGE OF ENGINEERING

UNIVERSITY OF ILLINOIS

1916

UNIVERSITY OF ILLINOIS

May 31, 1916

THIS IS TO CERTIFY THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

Leslie Monroe Gumm and Oral Albert Lansche

ENTITLED Further Development and Testing of a Direct Reading Dynamometer

IS APPROVED BY ME AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

DEGREE OF Bachelor of Science in Electrical Engineering

Chas R. Moore
Instructor in Charge

APPROVED: Ellery B. Paine

HEAD OF DEPARTMENT OF Electrical Engineering

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FURTHER DEVELOPMENT AND TESTING OF A DIRECT READING DYNAMOMETER.

I. INTRODUCTION.

During the years of 1914 - 15, P. J. Nilsen wrote a thesis on a machine designed to measure mechanical power directly. The investigation was not fully completed, and this thesis has for its object, the completion of such investigation.

II. SUMMARY OF PREVIOUS DEVELOPMENT.

A. Outline of Previous Work.

The previous work is briefly described by Nilsen as follows:- "The purpose of this thesis is to give the history of the development of an apparatus which measures mechanical power directly; that is, this dynamometer is to the transmission of mechanical power what the wattmeter is to the transmission of electrical power." In his thesis he gave a description of the various dynamometers in existence together with the fundamental conception of power upon which all have been based. He pointed out that previous to the present development, all so called dynamometers have measured merely torque or force, which is not power. The conception of the present machine was to measure power directly.

Moore in the Technograph of January, 1916, briefly describes the

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machine thus:- "The device as a whole consists of two small single phase alternators connected mechanically by a spring. The two armatures are connected in series with a voltmeter so that at any time the instrument reads the resultant voltage produced by the two alternators. Mechanical power is applied to one of the alternator shafts and delivered by the other with the result that the spring is deflected by an amount dependent on the torque transmitted. The voltages of the two machines are carefully adjusted to equal values by varying the field current through each". It is obvious that this equality of voltage holds for all speeds since voltage varies directly with the speed, and from the nature of the design the speeds of the two alternators are always equal. With the machine running light i.e. no power transmitted, one of the armatures which is made rotable on the axis of the shaft is turned until the voltage produced by it is exactly opposed at all times to the voltage produced by the other alternator. Evidently under these conditions, the resultant voltage acting on the instrument is zero. If now mechanical power is transmitted, the spring deflects allowing the voltage of the alternator on the driven side to move ahead of the other alternator by an amount proportional to the torque transmitted. A resultant voltage is thus set up in the circuit indicated by the voltmeter. On the assumption of sinusoidal waves of voltage produced by each machine, we can represent by vectors what takes place. Fig. 1 shows the vector relationship with the machine running light; Fig. 2, with a load transmitted.

Nilsen showed that for a range of 28° allowing an error of one per cent, E_r was proportional to both E_s and θ and therefore proportional to their product. Hence the machine measures, if properly calibrated, the product of speed and torque or power. Trigonometrically

Machine with Helical Spring.

Figure 1

Figure 2

it may be shown that $E_r = 2E_s \sin\frac{\theta}{2}$ or for angles less than 28° $E_r = 2E_s\frac{\theta}{2}$. However when an attempt was made to read the value of E_r using an ordinary voltmeter, the effects of the instrument were very noticable as will be pointed out later, but apparently in Nilsen's development other difficulties, which will be referred to later, required attention first.

One of Nilsens greatest difficulties seemed to be mechanical; the matter of a suitable spring. Obviously such a spring must satisfy the following requirements:-

(a) The angular deflection or twist must be proportional to the torque producing it over a fairly large angle - that is, the spring should obey the straight line law.

(b) The spring should give the same angle - torque characteristics for both positive and negative stress, so that the power meter may be operated in either direction.

(c) The spring must return to the zero position when the torque is removed.

(d) The effect of centrifugal force must be practically eliminated since the rotative speeds vary over a wide range.

(e) The design should be simple so that changes necessary to accomodate a wide range of torque may be easily and quickly made.

(f) The spring must occupy only a limited space.*

After testing out a number of spring forms including a flat steel blade, a double flat steel blade, and a helical spring, the final design tested and adopted was that shown in Fig. 3. "It was termed a "squirrel cage" spring since it consisted of a set of parallel rods fastened rigidly at one end in holes near the outer periphery of a flange or disk, the opposite ends being inserted in corresponding chamfered holes in a similar opposed flange. One of these flanges is

*American Machinist, February, 1916.

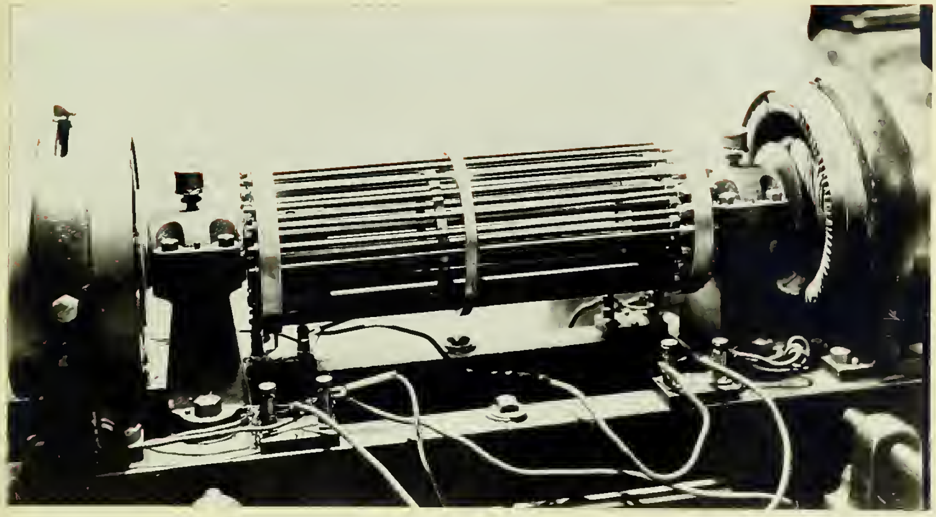

Fig. 3.

mounted on the driving shaft and the other on the shaft to which torque is to be transmitted."* When a torque is now applied the rods are bent at right angles to the radius of the flange. "Each rod may be considered as a simple beam in flexure so that the formula

$$D = \frac{L}{3}\ \frac{PL^3}{EI} \quad \text{may be used}$$

where D = deflection in inches

P = load in pounds at end of rod

L = free length of rod

E = modulus of elasticity in tension

I = moment of inertia of rod section.

This type of spring is not affected by centrifugal action, obeys a straight line law when deflected in either direction, and larger powers may be transmitted by the insertion of more rods. It is cheap and convenient and seems to answer in every way the requirements of this power meter." § We shall not attempt to give in this thesis a complete history of previous work on springs as the one referred to above met all the requirements laid down.

B. Notation of Derivations and Equations.

The underlying theory upon which all power measurements must be based is that power is the rate of doing work. Work, moreover, is a force acting through a distance. Reducing power to its fundamental or dimensional units we would have:-

$$P = \frac{W}{t} = \frac{FL}{t} = \frac{MaL}{t} = \frac{MvL}{t^2} = \frac{ML^2}{t^3}$$

where P = power in foot pounds per minute

W = work in foot pounds

F = force in pounds

v = velocity in feet per minute

*"American Machinist" Feb. 24, 1916.
§ Nilsen

[illegible]

t = time in minutes

a = acceleration in feet per minute per minute.

L = distance in feet

M = mass in pounds.

Referring this to rotary motion

If R = radius at which F is acting

N = speed in revolutions per minute

T = torque exerted on shaft in foot pounds

K = a constant

Then $W = FL$

$= Fvt$

While power $= \frac{W}{t} = \frac{Fvt}{t} = Fv$

For rotary motion $Fv = F\,2\pi RN$

But $FR = T$

Therefore $P = 2\pi NFR = 2\pi NT$

Moreover Horsepower $= \frac{2\pi NT}{33000} = KNT$

Power therefore as applied to rotary motion is proportional to the product of torque and speed. Instantaneous power will be proportional to instantaneous torque multiplied by instantaneous speed.

The present machine is designed with the view of utilizing this fact.

III. IMPERFECTIONS APPARENT IN PREVIOUS DEVELOPMENT.

A. Results Obtained in Actual Machine.

Experiments with the actual machine show that instead of reading the developed voltage E_r, a different voltage is obtained. This can be explained in the following way:- In order to measure E_r we must insert a voltmeter in the circuit. This instrument has practically resistance only while the armatures have both reactance and resistance. Now the voltmeter will read only IR drop within itself. Therefore the voltage shown by the instrument may be made to approach the developed voltage, but can never equal it. This is clear from Fig. 4. On the old design the reactance and resistance of the armatures were approximately 70 ohms each. Consequently, it was found necessary to purchase a very sensitive voltmeter of 500 ohms resistance in order to minimize the effect of armature impedence. The desired end was that $E_{inst.} + I\,R_{arm}$ should not differ from E_R by more than 1% and the reactance of the armature was too high to allow this if we used an ordinary commercial instrument. This reactance was cut down as will be shown later until its effect was so small that an ordinary commercial voltmeter could be used with excellent success.

B. Imperfection in Poles.

The poles on the original machine were what is known as the concentrated type. Fig. 5 shows the pole. In this type the

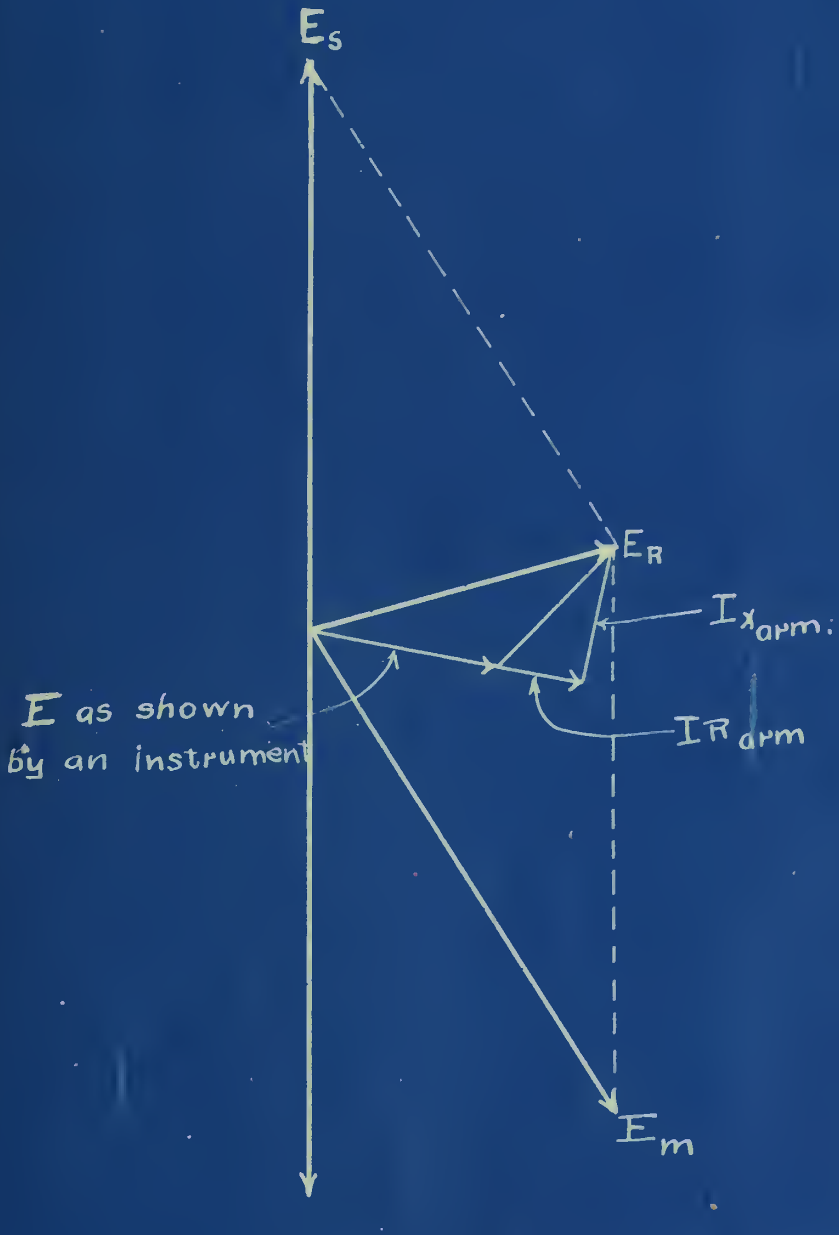

Figure 4

Fig. 5.

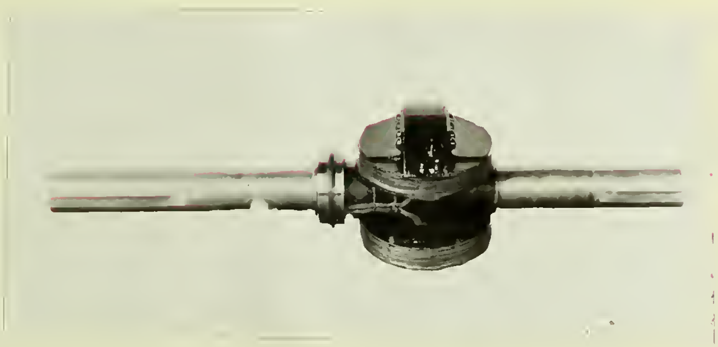

Fig. 5a.

field coils encircled the entire flux of each pole, and the proper distribution of flux density was secured by means of the suitably shaped pole piece or "shoe". It was thought in the original design that proper flux distribution could be obtained experimentally by the pole shaping. However, it was found very difficult to shape the pole properly.

The wave of flux distribution given by the original pole is shown in Fig. 6, film 6. It was obtained by means of an oscillograph and a small test coil wound around the armature core. It will be noted that the curve is more or less rectangular in shape, the sharpness being dependent upon the shape given the pole shoe and the magnetic saturation of the pole tips. In order to make the machine small in diameter, high magnetic densities had to be employed, and the pole tips had necessarily to be made rather sharp to find room for the exciting coils. For these reasons, the original pole did not give the predicted flux distribution, but that shown in Fig. 6, film 6. Furthermore, it was found that shaping the pole tips did not have the usual effect. Experiment showed that whereas shaping the pole tips modified the upper corners and the height of the flux wave, it did not materially change the flux densities in the space between the pole tips, i. e., the shape of the curve near the zero line was unaltered.

It will be noted that the outer edge of the exciting coils run very closely to the armature surface, a fact which limits the spread of the flux since the magnetizing coils must encircle the flux.* Therefore, to secure the necessary flux densities in the space between the pole tips, it would have been necessary to change

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* "Moore" in Technograph, January, 1916.

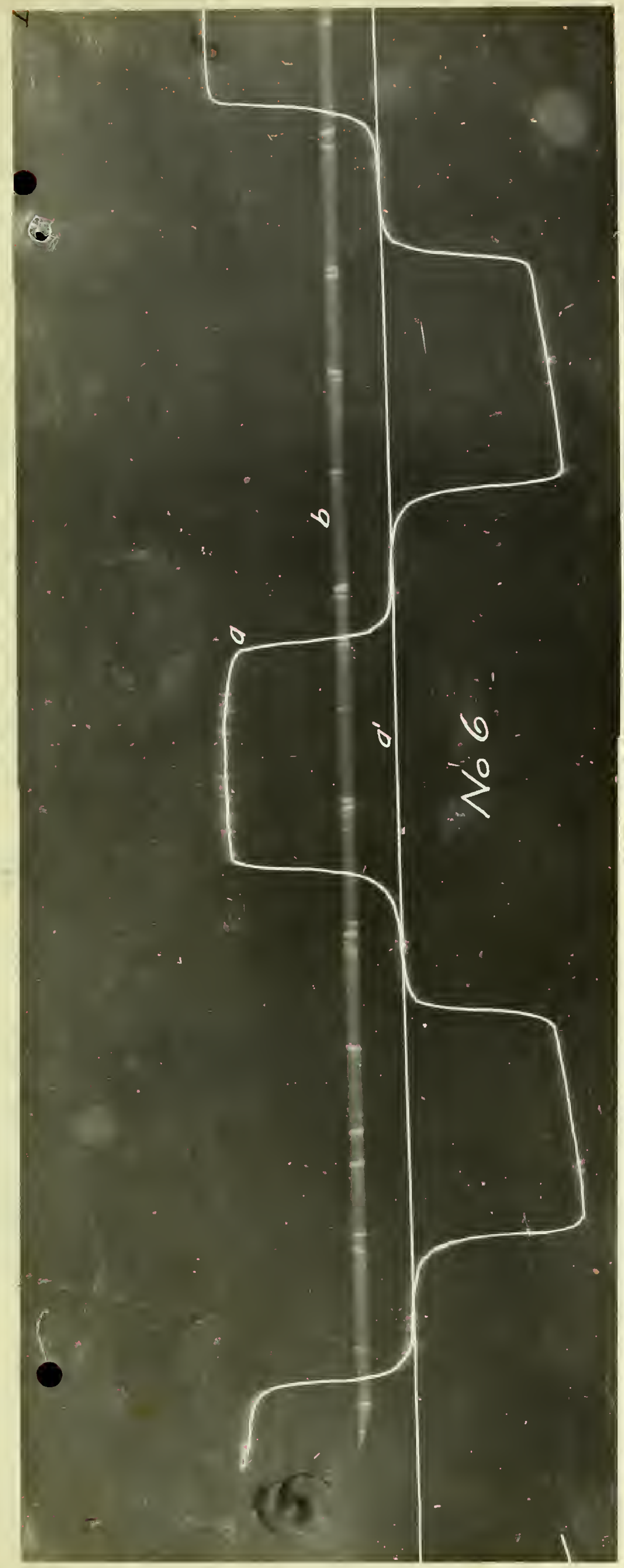


Fig. 6.
Film 6.

the form and dimensions of the magnetizing coils, a condition seldom if ever met with in alternator construction. It may, therefore be said that the shape of the flux distribution curve given by the "concentrated" type of pole as originally employed, depends upon three things:-

1. The magnetic saturation of the pole tips.
2. The shape of the pole shoe.
3. The position of the exciting coil.

It was thought that instead of making the changes indicated, an easier solution would be to use the "distributed" type of pole. However, some further experiments were made to determine what improvement in wave form of voltage might be expected using the concentrated pole, if armature windings covering various percentages of pole pitch were employed. These experiments, together with the development of the distributed pole will be discussed later.

C. Imperfection in Armature.

The armature as already developed is shown in Fig. 7 and 8. It was not found advisable to make any changes in its mechanical form. However, tests were made as will be indicated later to determine whether and how much skewing of the windings would help in the matter of the wave form.

As pointed out under III-A the inductance of the armature was high, and tests were made with a view of lowering this inductance.

Fig. 7.

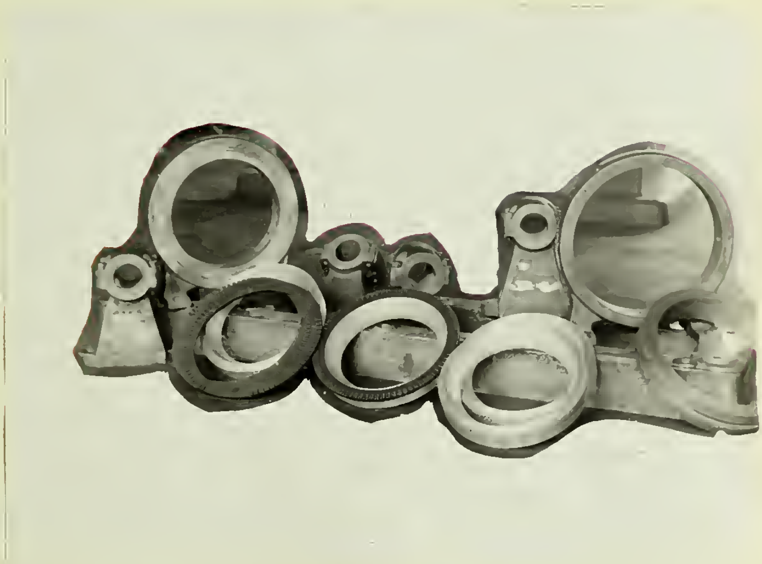


Fig. 8.

IV. REDESIGN WITH THE VIEW OF IMPROVEMENT.

A. Skew Winding Tests.

Before making the change from the concentrated pole design, it was thought advisable to determine the effect of spread of armature winding on wave form, and also the effect of skewing the winding.

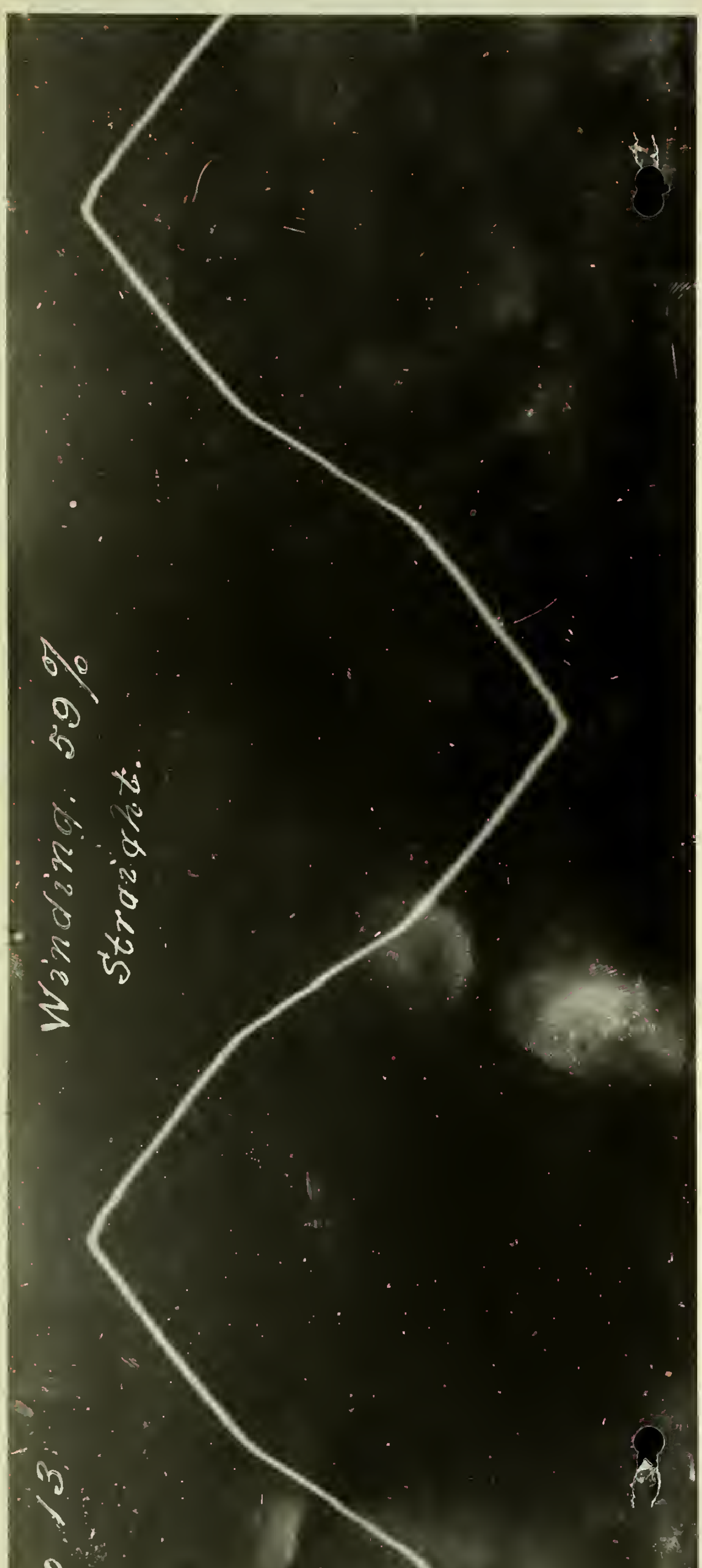
In film 16 the machine was rewound with No. 17 wire skewed about two-tenths inches across the armature face. In order to study the effect of spread conductors were removed from both sides of the windings. The spread was varied from 54% to 70% of the pole face with results shown in films 13, 14, and 15. With the continued increase in spread the straight parts of the voltage wave along the sides seemed to shorten, but the flat top lengthened as might be expected from the wave of flux.

We investigated skewing the armature winding by means of "test windings". Such skewing added little to the wave form as is shown in film 16 and 17, because we could not skew enough to bridge the whole space between the pole tips.

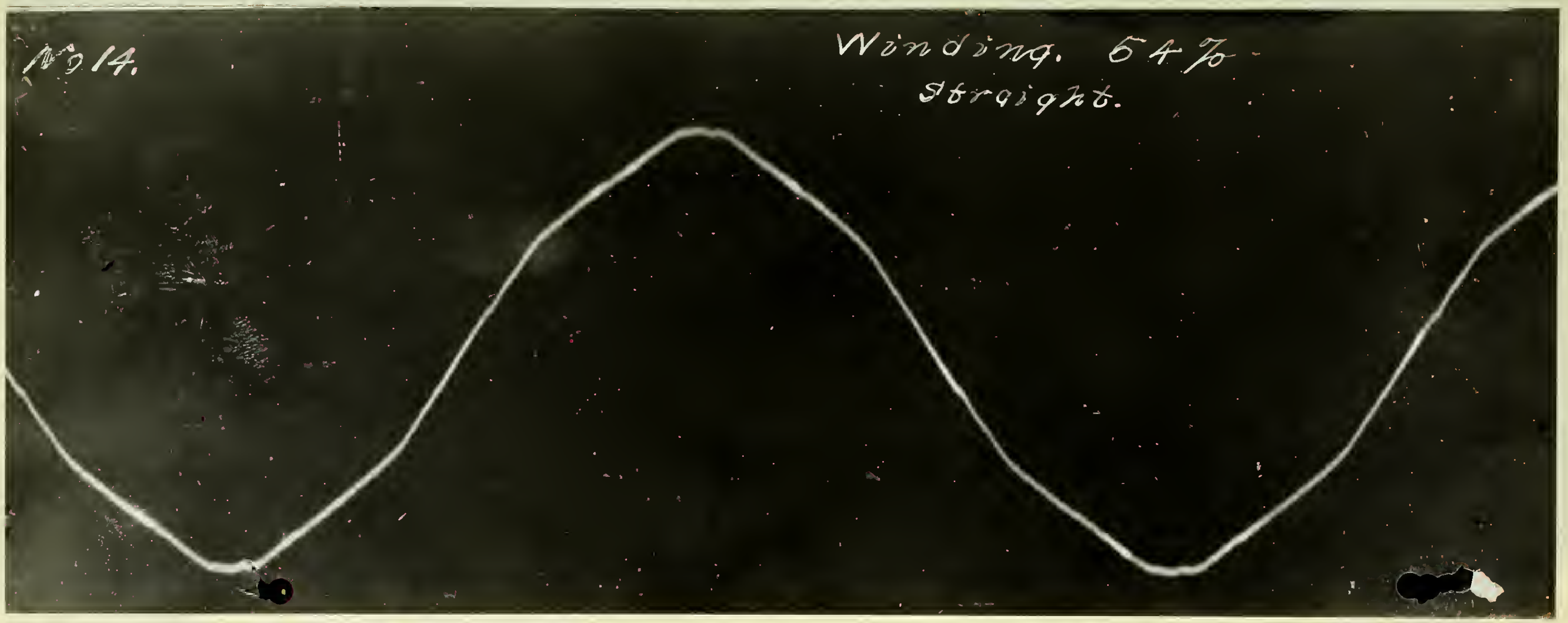
In view of the above it was decided to change the pole design before going further.

B. Development of the Distributed Pole.

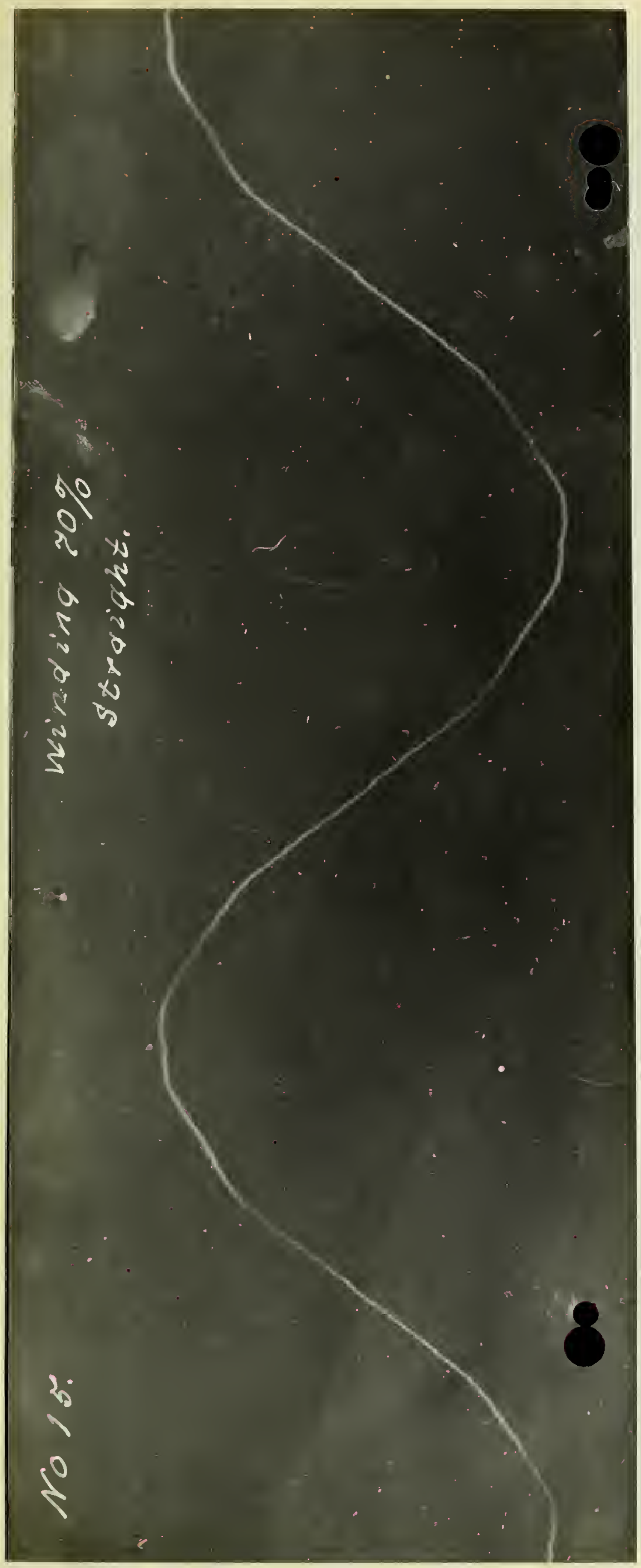
As has been pointed out, several facts indicated that the concentrated pole design could not be used conveniently. Hence



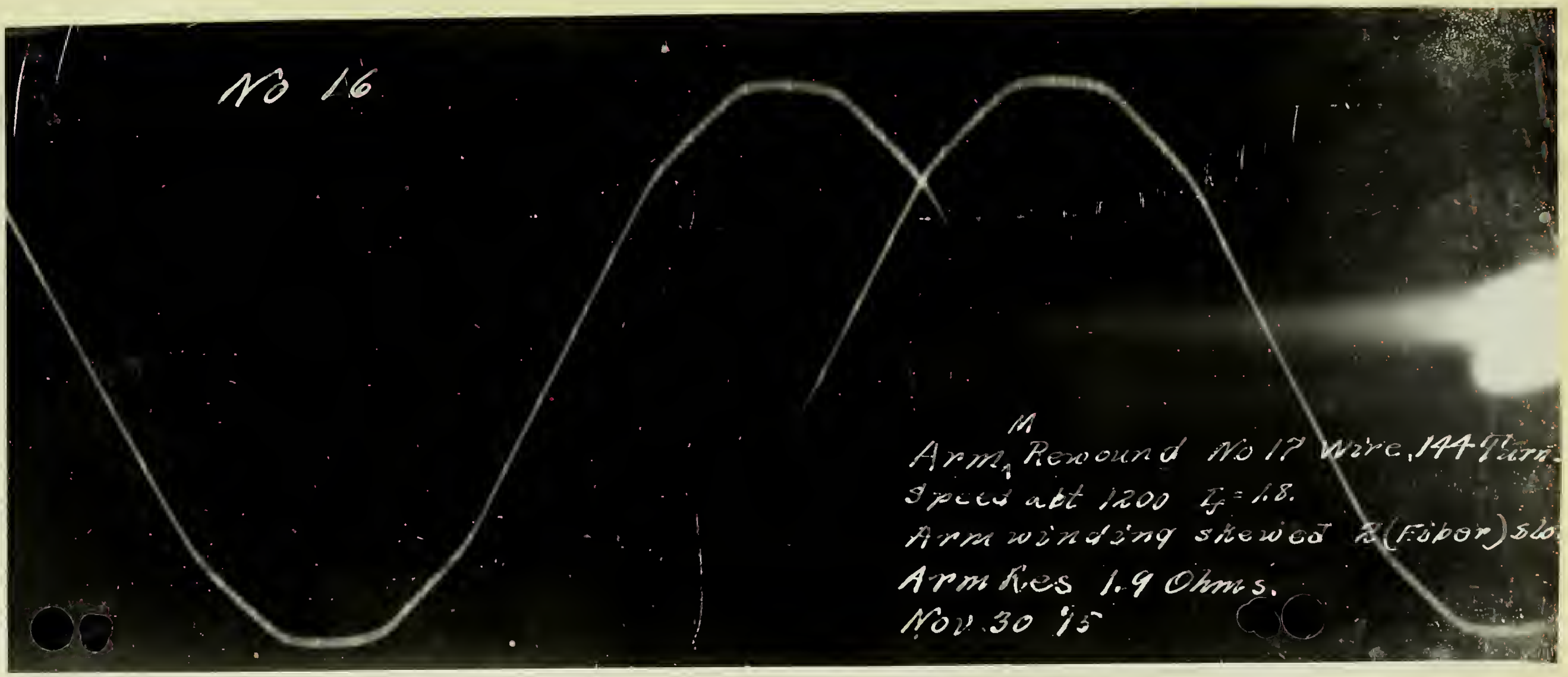
Film 13.



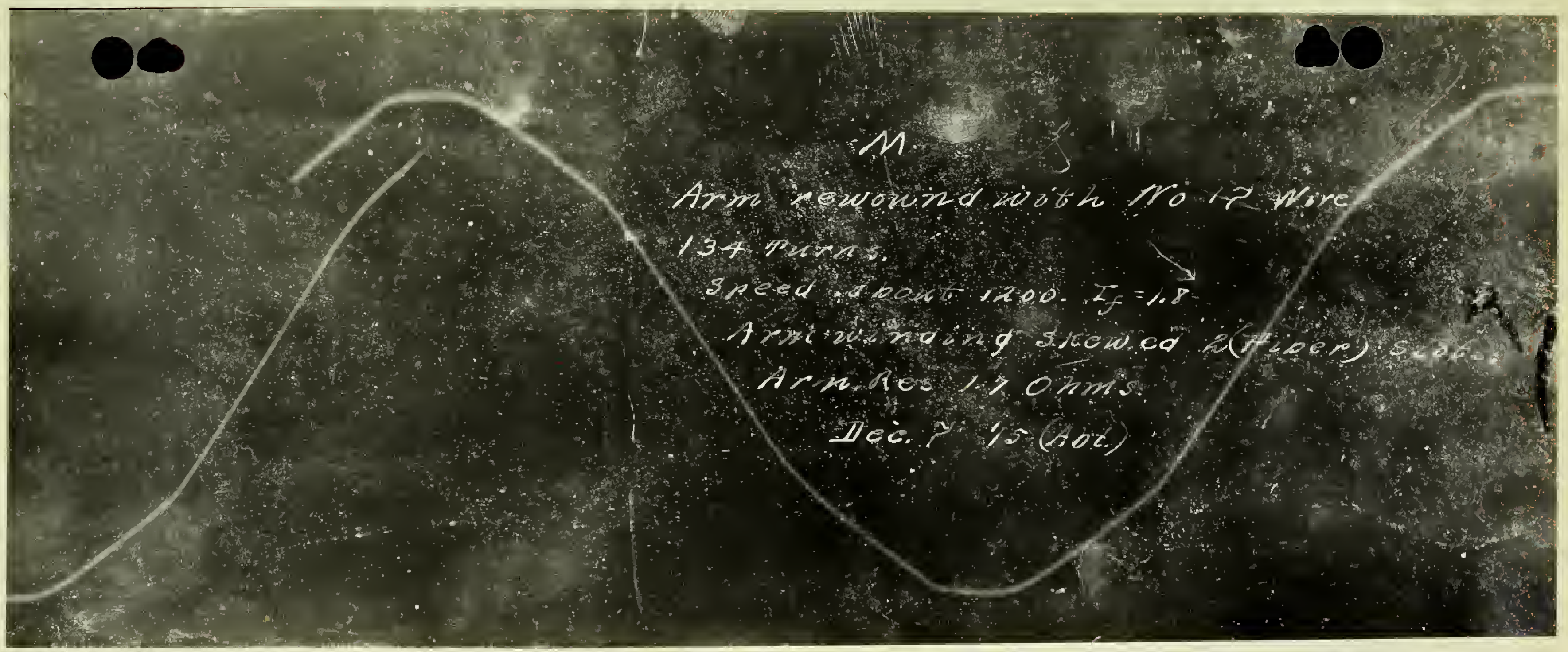
Film 14.



Film 15.


No 16
Arm, Rewound No 17 wire, 144 Turn
Speed abt 1200 $I_f = 1.8$.
Arm winding skewed 2 (Fiber) slo
Arm Res 1.9 Ohms.
Nov 30 '15

Film 16.


M.
Arm rewound with No 17 Wire
134 Turns.
Speed about 1200. I_f = 1.8
Arm winding skewed 2 (Fiber)
Arm. Res 1.7 Ohms.
Dec. 7 '15 (Hot.)

Film 17.

our attention was directed to the distributed pole.

A distributed pole was worked out on the basis of sine wave flux distribution thus:

A sine wave was drawn as shown in Fig. 9. Steps A, B, C, D, and E were laid out arbitrarily on it, corresponding to positions on the pole face. Then at A enough ampere turns were allowed to bring the m.m.f. up to a value proportional to the height of A indicated on the scale at the left. When at B enough turns were added to bring the m.m.f. up to a value proportional to the difference between B and A. The process was continued for positions C, D, and E. The pole was slotted as shown in Fig. 13, and the winding put in by placing the conductors in symmetrical slots.

Hence, we have produced a pole of uniformly decreasing and increasing m.m.f. according to a sine law. Fig. 10 shows the completed pole structure.

From the winding the flux distribution was calculated and predicted as follows:

$$\varphi = \frac{F}{R} = F \times P \qquad R = \frac{L}{A}$$

L = length of air gap.

F = magnetomotive force.

R = reluctance.

P = permeance.

Consider a section of the slot as shown in Fig. 12.

Between the slots the air gap (lg) is uniform. In the slot for any distance r from the edge of the slot, the length of the flux line = $Lg + 1/4 \;\; 2\pi r = Lg + \frac{\pi r}{2}$.

Considering the increment of area dr for unit length of the pole, $$R = \frac{LG + \frac{\pi r}{2}}{dr}$$

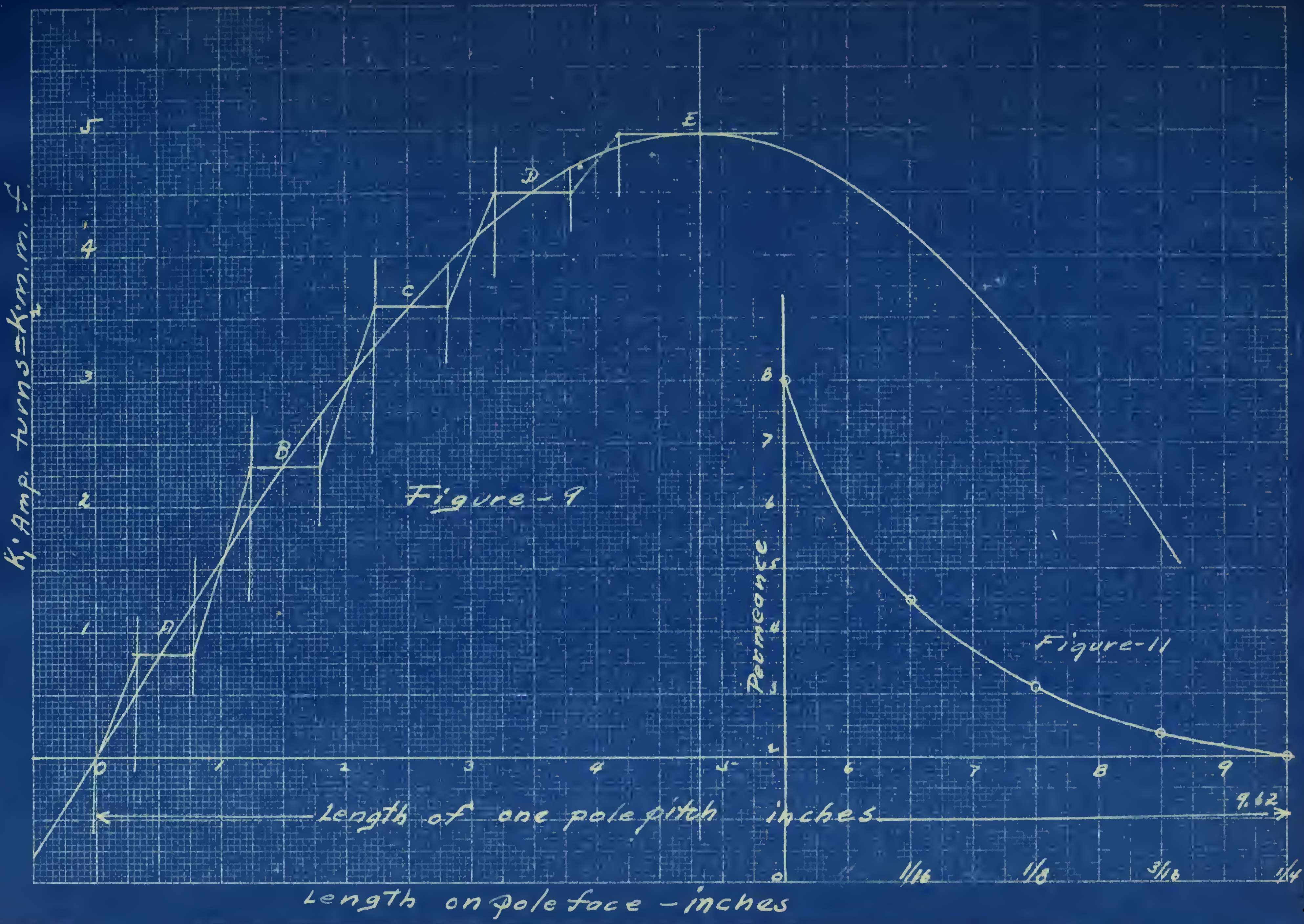

K, Amp. turns=K.m.m.f
Figure-9
Figure-11
Permeance
A
B
C
D
E
Length of one pole pitch inches
9.62
Length on pole face - inches
0
1
2
3
4
5
6
7
8
9
1/16
1/8
3/16
1/4

Fig. 10.

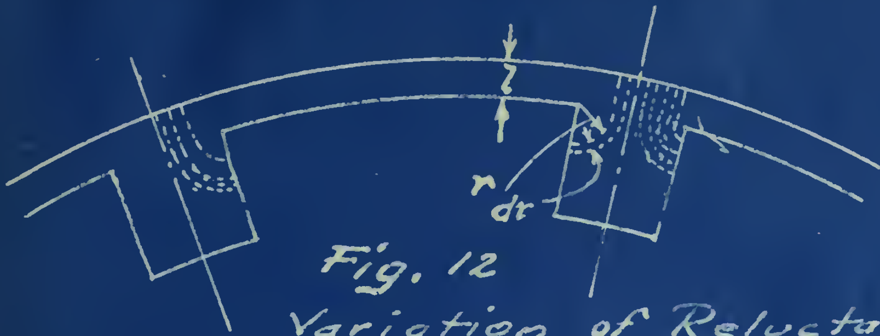


Fig. 12

Variation of Reluctance over the Pole Face.

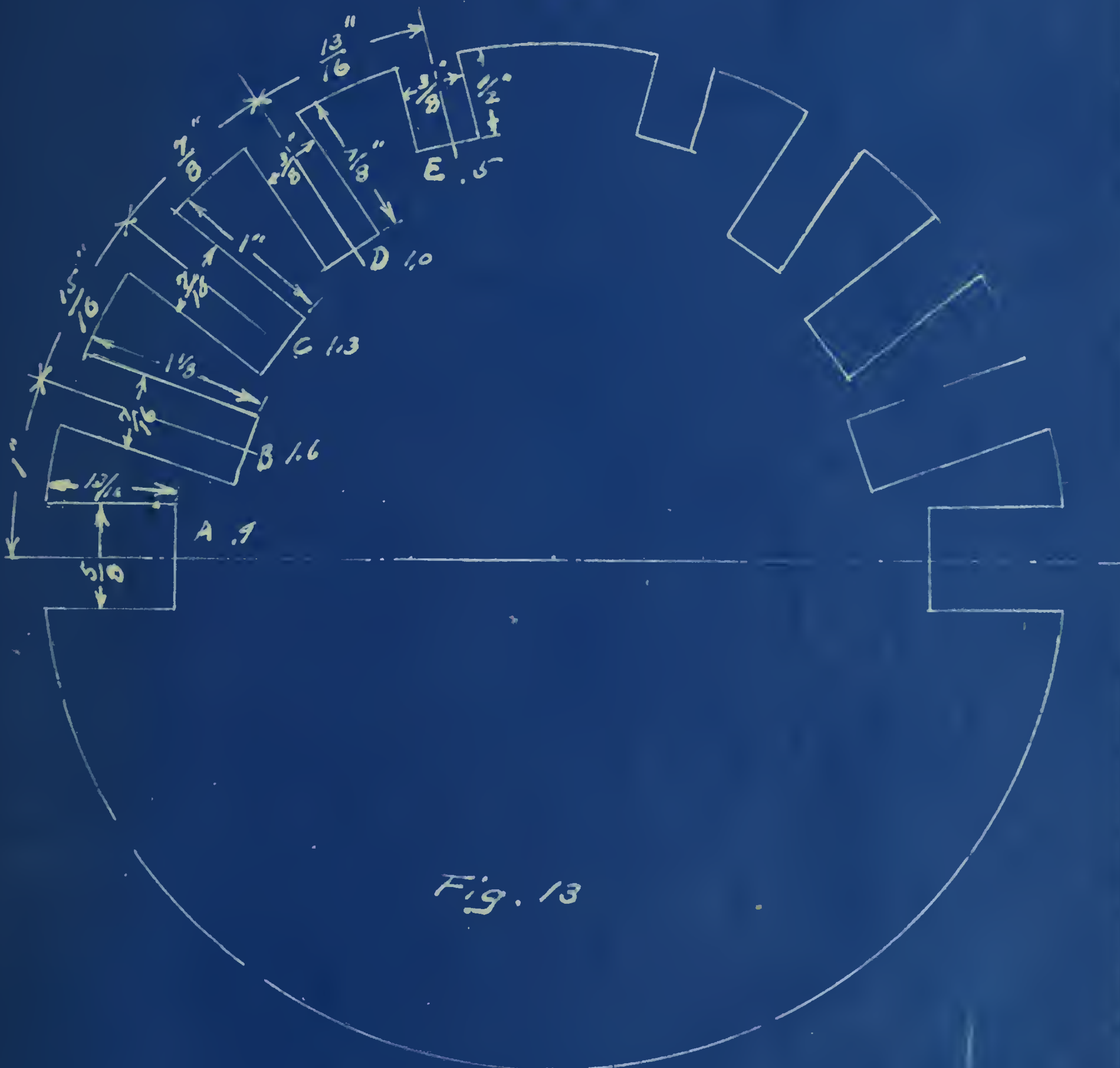


Fig. 13

Slotting of Pole.

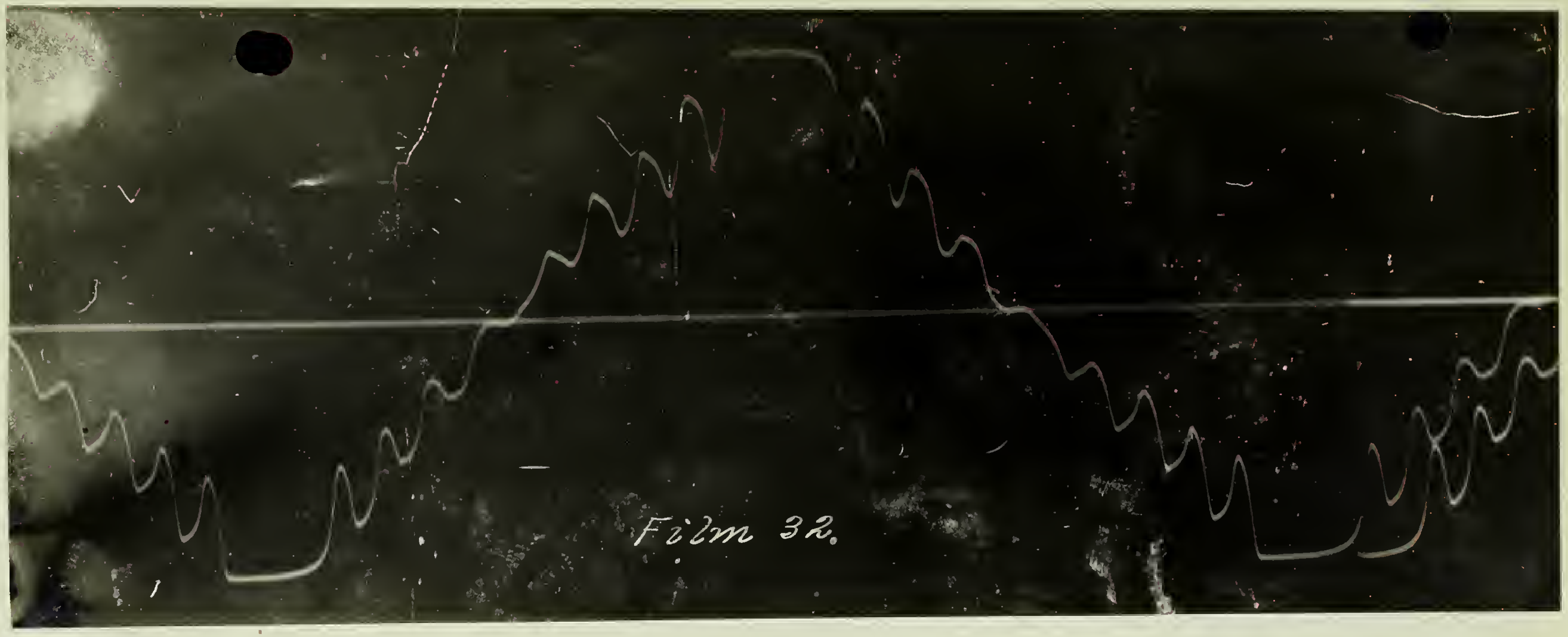
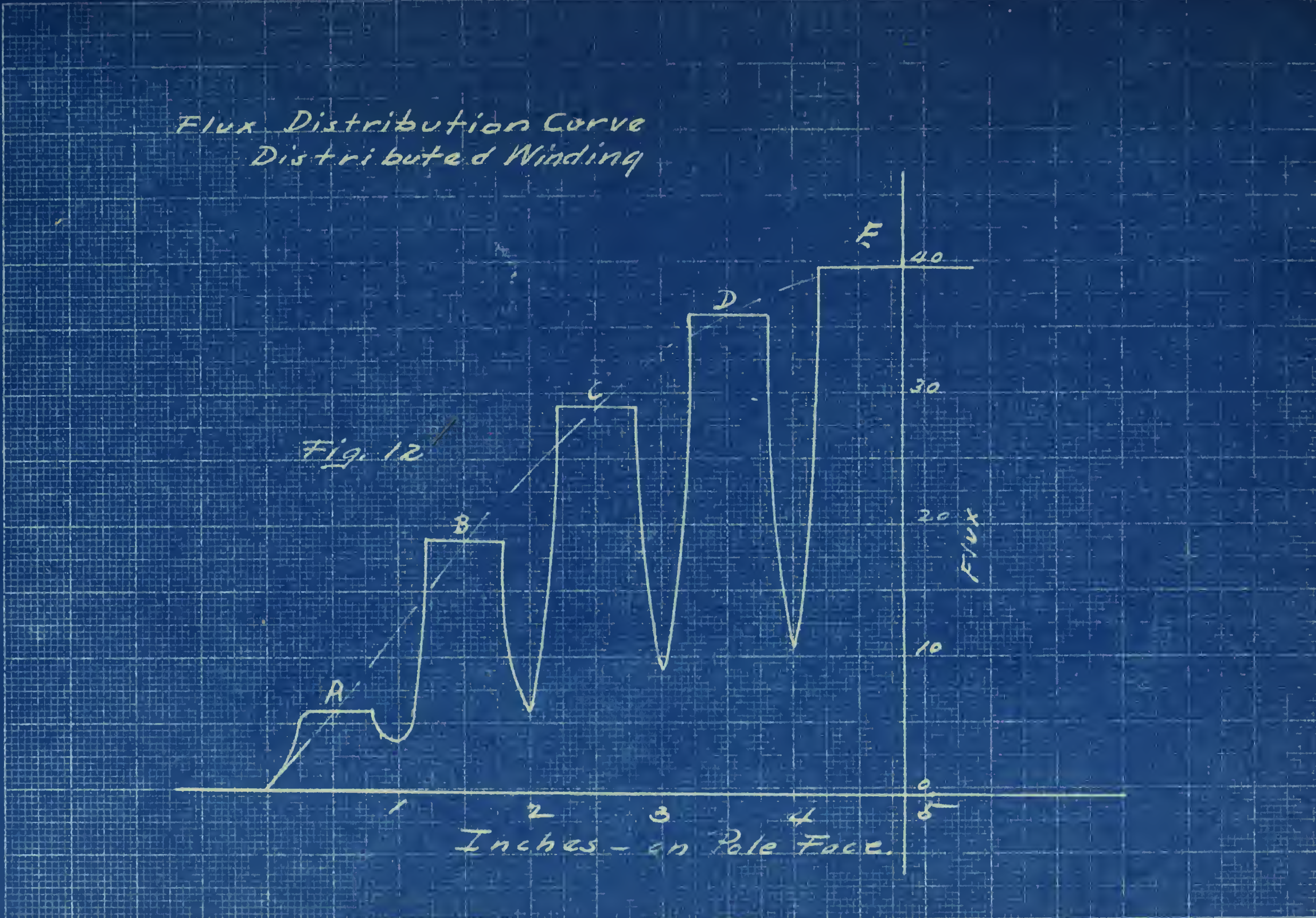


Fig. 13.
Film 32.


Flux Distribution Curve
Distributed Winding
Fig. 12
A
B
C
D
E
Flux
0
10
20
30
40
1
2
3
4
5
Inches - on Pole Face.

$$P = \int \frac{1}{\frac{Lg + \frac{\pi r}{2}}{dr}} = \int \frac{dr}{Lg + \frac{\pi r}{2}} = \int \frac{2\,dr}{Lg + \pi r}$$

$$= \frac{2}{\pi} \int \frac{\pi dr}{2Lg + \pi r} = \frac{2}{\pi} \log \left(2Lg + \pi r \right)\Big|_{R_2}^{R_1}.$$

From this equation values of permeance were calculated and plotted in the curve Fig.11.

The flux between two adjacent poles is uniform as shown at A. Variations for slots are calculated by the use of permeance values already determined.

The flux distribution as predicted is shown in Fig. 12! The flux wave while in general a sine wave, has irregularities due to the slotting as predicted. Fig. 13 shows the actual flux distribution as given by an oscillograph.

C. The Development of the Armature.

It is evident that each armature conductor if wound parallel to the axis would give a wave of e.m.f. exactly similar to the flux curve. In order to eliminate the irregularities, the conductors were caused to bridge the pole slots completely.

With the distributed pole, the skew provided a bridge for the conductors over the slot. The skew it would seem must be equal to the slot width. But in our case we did not make the skew quite so much. The effect of bridging is assisted by the leakage flux as follows:

Due to the high reluctance of the air gap the flux must fringe out over the edge of the armature face. Hence some of the fringing flux will cut the ends of the conductors and the effect will be the same as if the windings were given a greater skew and the flux did not fringe.

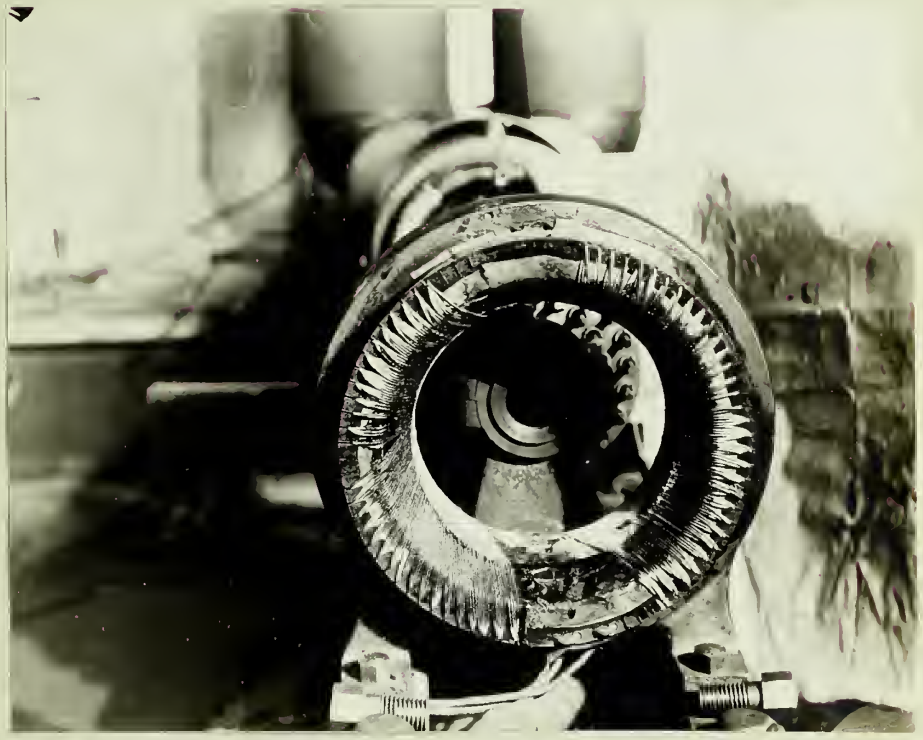


Fig. 12A.

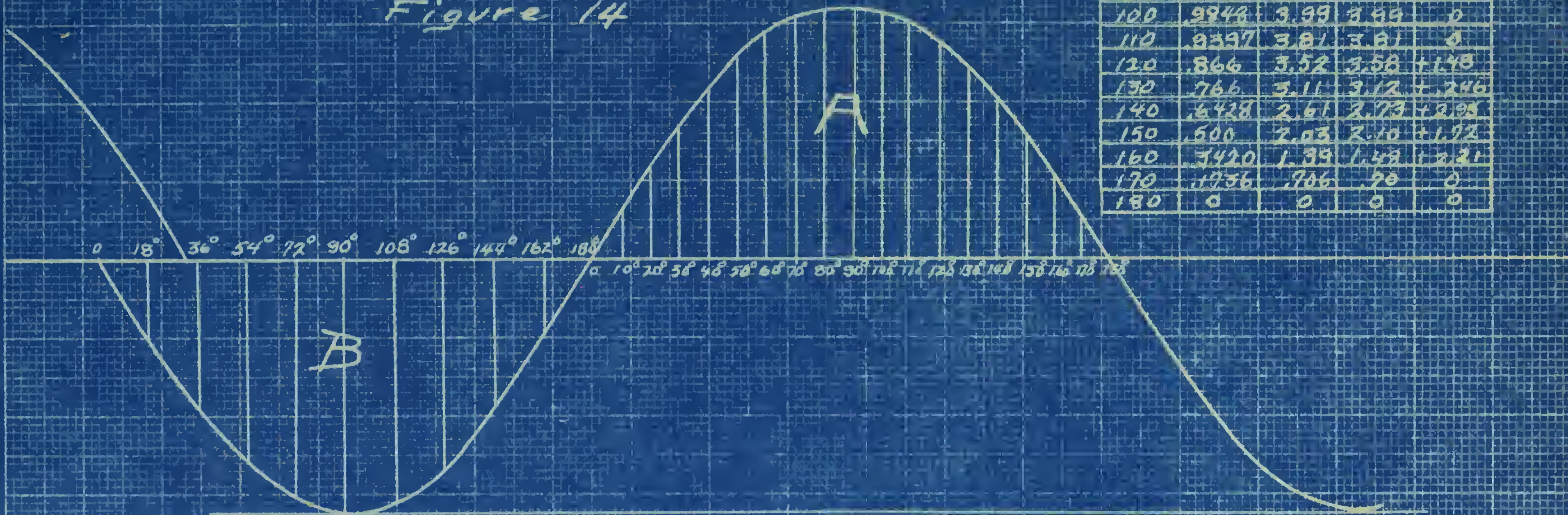
Near Sine Wave

Film 30

Divided for careful analysis

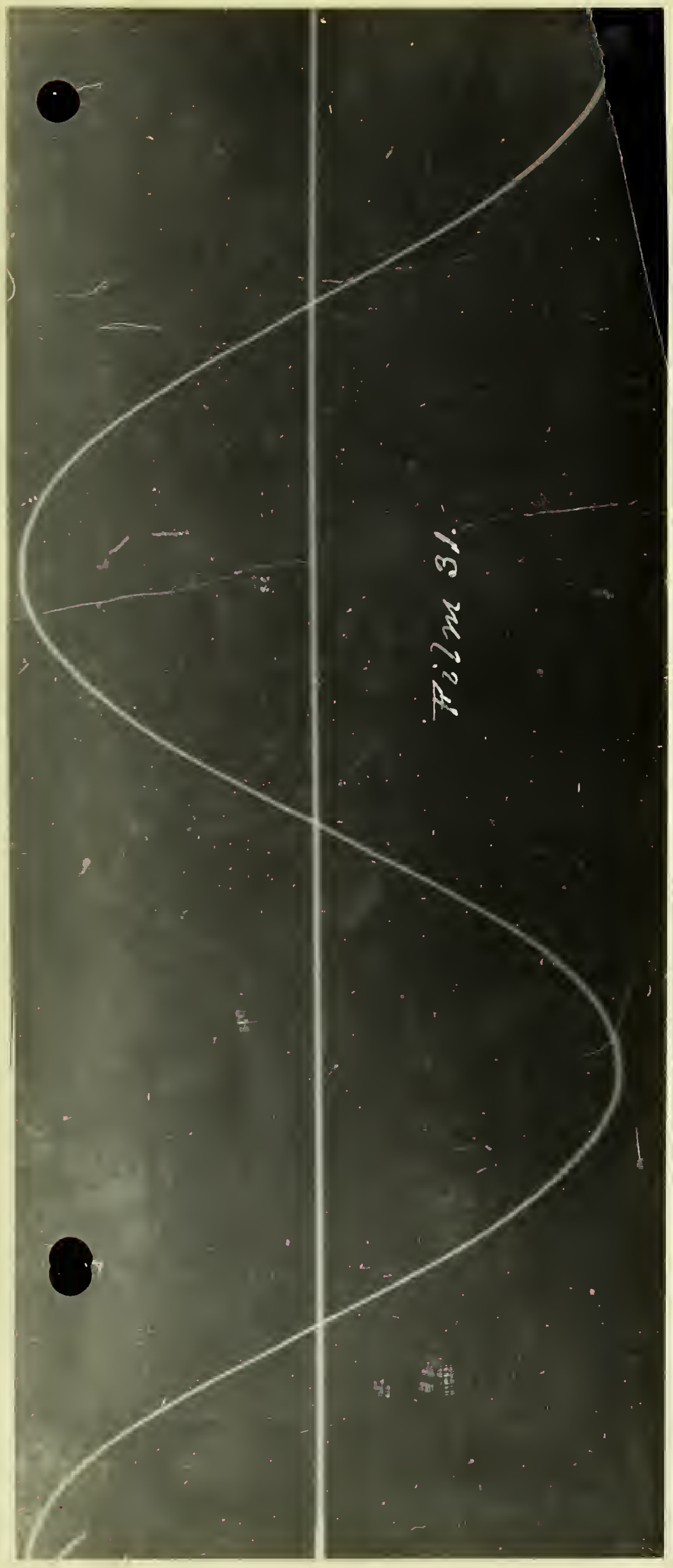
Figure 14

Degrees		Calc.	Meas.	Error
0	.000	0	0	0
10	.1736	.706	.75	+1.08
20	.3420	1.39	1.44	+1.23
30	.500	2.03	2.15	+2.86
40	.6428	2.61	2.7	+2.22
50	.766	3.11	3.16	+1.23
60	.866	3.52	3.53	+.246
70	.9397	3.81	3.80	-.246
80	.9848	3.99	3.98	-.246
90	1.000	4.06	4.06	0
100	.9848	3.99	3.99	0
110	.9397	3.81	3.81	0
120	.866	3.52	3.58	+1.48
130	.766	3.11	3.12	+.246
140	.6428	2.61	2.73	+2.95
150	.500	2.03	2.10	+1.72
160	.3420	1.39	1.48	+2.21
170	.1736	.706	.70	0
180	0	0	0	0

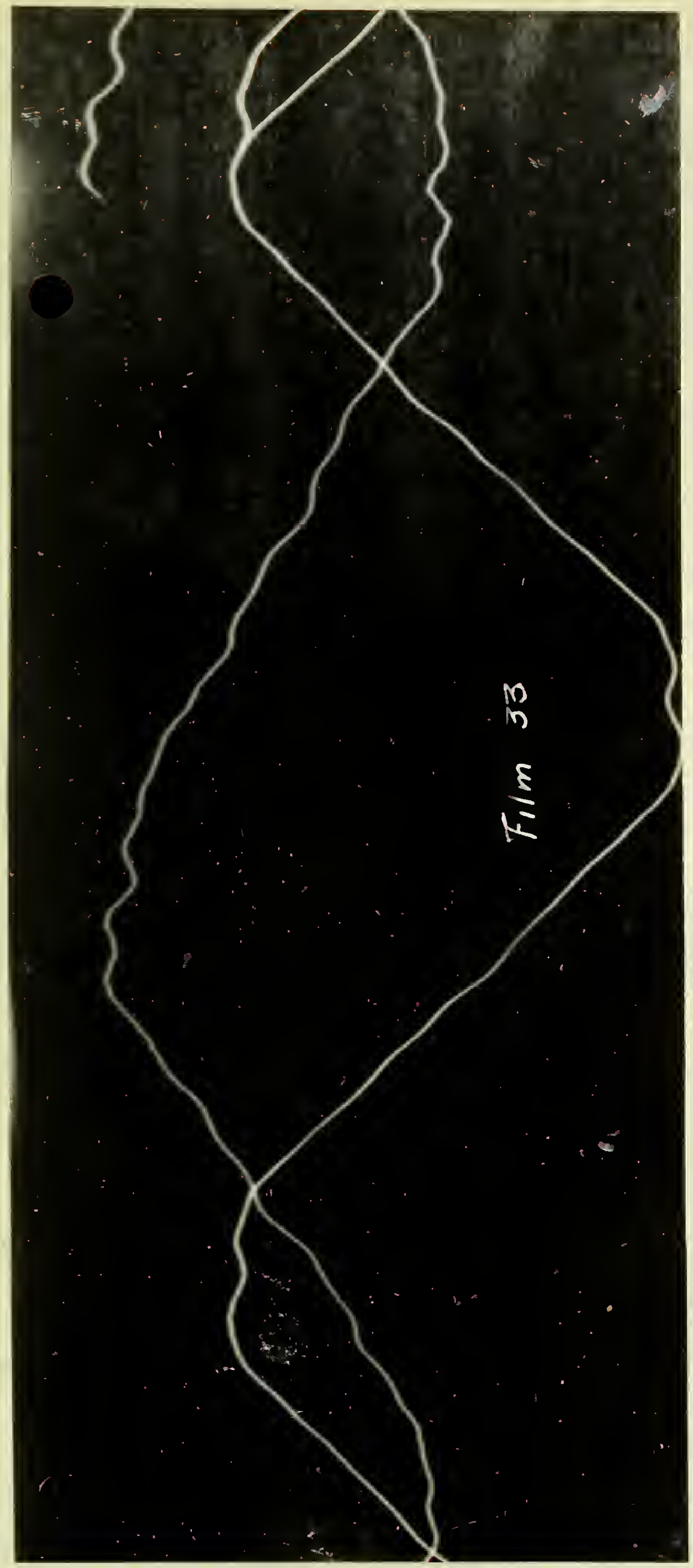


Degrees	Sin θ	E Sin θ Calc.	E Sin θ Meas.	% Error
18	.304	1.268	1.31	+.33
36	.588	2.410	2.48	+.419
54	.809	3.317	3.41	+3.6
72	.951	3.90	3.96	+1.54
90	1.000	4.10	4.10	0
108	.961	3.90	3.88	-.514
126	.809	3.317	3.33	+.255
144	.588	2.410	2.50	+2.68
162	.304	1.268	1.37	+.63
180	0	0	0	0

Film 30.



Film 31.



Film 33.

It is obvious that the amount of spread given the armature winding is immaterial.

Fig. 12-A shows the armature as completed. One hundred twenty-five turns in a single layer were used. As will be pointed out later (V-C) this winding had considerably less inductance than the original one which was of considerable value. Fig. 14 shows the final wave form given by this armature winding and the distributed pole.

Measurements from this wave together with a tracing of the original are shown in Fig. 14.

Films 30 and 31 show the wave forms. It is evident that the wave is an accurate sine curve within the limits of the oscillograph.

Resultant waves taken at different speeds of the powermeter and different deflection of the spring are shown in Film 33.

D. <u>Development of the Circle Diagram for Varying E.M.F. and Varying Reactance, and the Extent to Which We Can Use "Circular" Current with Straight Line Relations</u>.

We found in this machine a condition of varying e.m.f. and varying reactance -- both varying directly with the speed -- producing a current that varies according to a law that we had not previously considered.

Our conditions are shown in Fig. 15, 16, and 17.

Here

$$E = -n\frac{d\varphi}{dt} \quad \text{and } X = 2\pi f L.$$

L = inductance.

If E were constant and X varied we would have the circular locus ABC for the current. But since E and X both vary directly

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

with the speed, the current varied according to the circular locus -- ADE as indicated in the following calculations:

$$x = nX \qquad e = nKX$$

$$\tan \varphi = \frac{nX}{R} \qquad nX = R \tan \varphi$$

$$I = \frac{nKX}{\sqrt{R^2 + n^2x^2}} = \frac{K R \tan \varphi}{\sqrt{R^2 + R^2 \tan^2\varphi}} = \frac{K R \tan \varphi}{R\sqrt{1 + \tan^2\varphi}}$$

$$= \frac{K \tan\varphi}{\sqrt{1 + \tan^2\varphi}} = \frac{K \tan\varphi}{\sqrt{\sec \varphi}} = K \frac{\sin \varphi}{\cos \varphi} \cdot \frac{\cos \varphi}{1} = K \sin \varphi.$$

x = reactance at any speed

e = e.m.f.

K = constant

X = reactance at some definite speed

n = speed

φ = angle of lag.

Our theory is substantiated by the curves shown in Fig. 18 . The following is the data from which the curve is plotted:

Armature Wound Skew with 134 Turns No. 17 Wire.

Speed	Ia	Speed	Ia	Speed	Ia
47	4.8	1450	1063.	2180	1265
595	5.87	1575	1105.	2300	1300
595	5.85	1720	1175.	2440	1328
725	6.8	1810	1190.		
860	7.62	1945	1227.		
1010	8.5				
1190	9.51				

In order to show the circular locus on a large scale we short circuit the machine through an ammeter and draw current with the smallest possible resistance in the armature circuit. In Fig. 18 the data is obtained with an ammeter in the circuit.

If a voltmeter be used R is greatly increased and the current taken is greatly decreased for a given voltage. The effect that would take place is shown in Fig. 17,, which is drawn on a much

smaller scale than Fig. 16 or 18.

Under operating conditions a voltmeter draws such a small current for the highest speed that we may, with a sufficient degree of accuracy, consider the current to vary with a straight line relation.

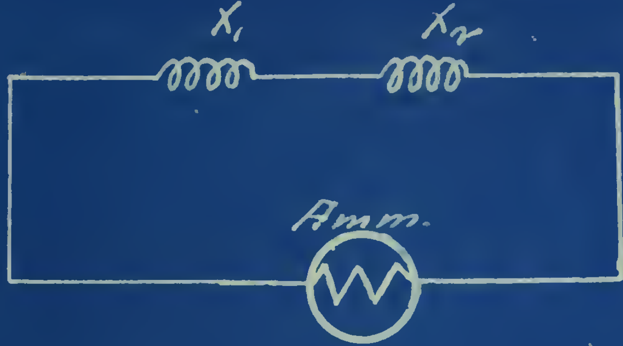


Fig. 15

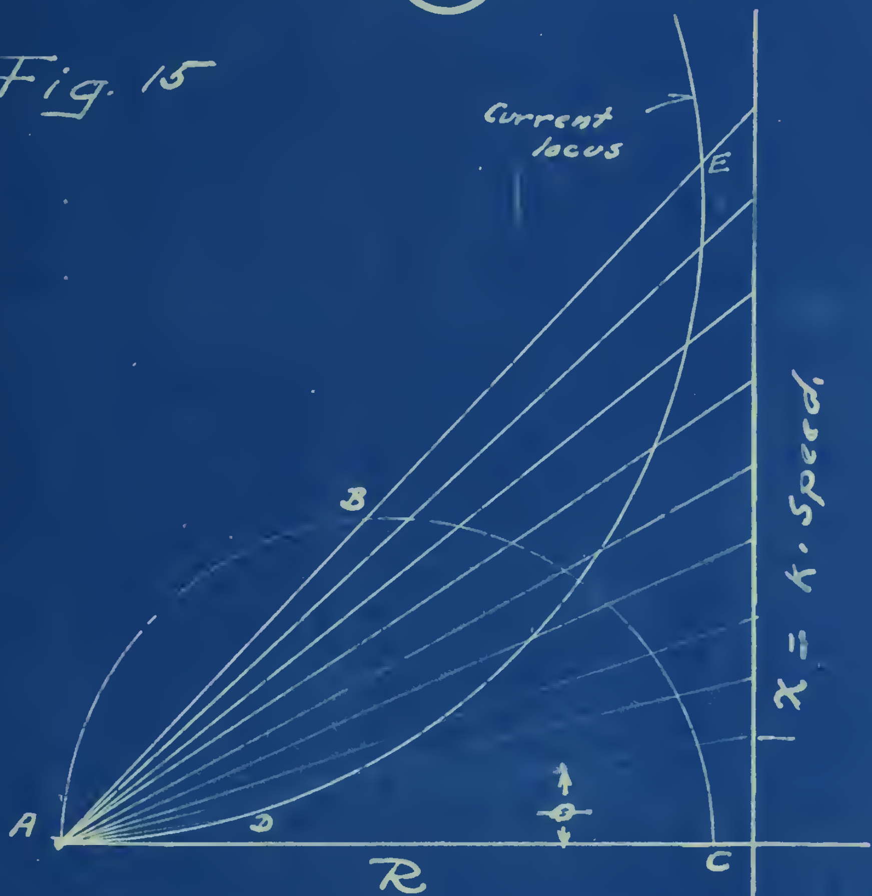


Fig. 16

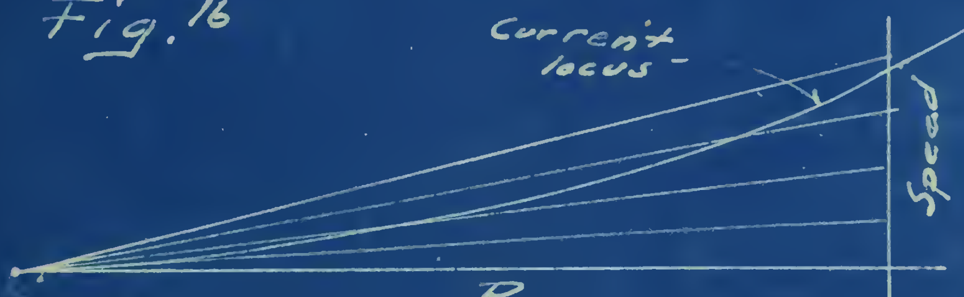
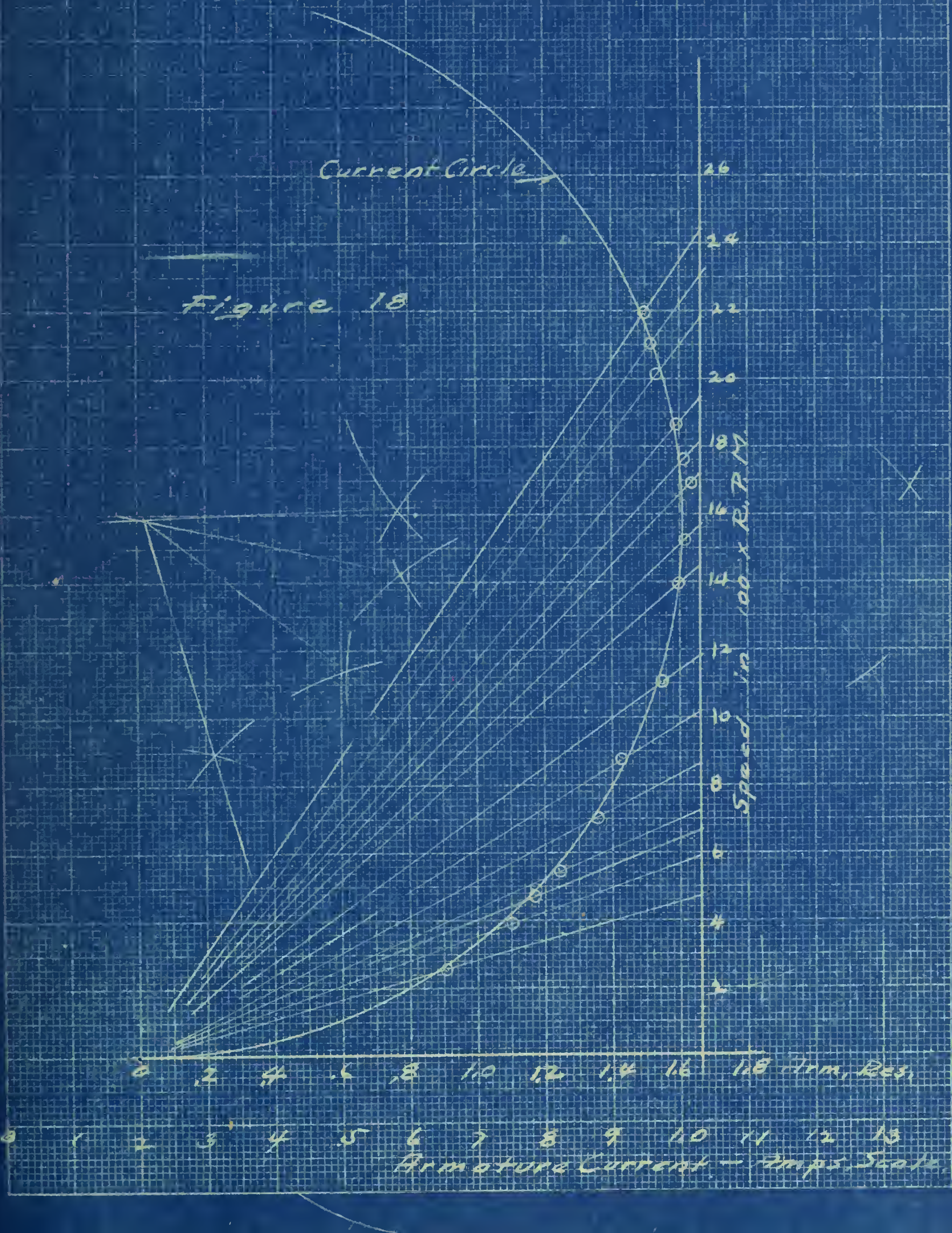


Fig. 17

Curve Showing Relation of Current with Varying E.M.F. and Varying Reactance.



V. TESTS.

A. Tests on Springs.

In order that we might be assured of the satisfactory operation of the spring we conducted tests for permanent set, and to determine whether the spring obeyed a straight line law.

1. Tests of Rods as Such.—The spring as originally used consisted of 24 - 1/4-inch drill rods at a distance of 2-21/32 inches along the radius from the center and 16 - 5/16-inch drill rods at a distance of 2 1/8 inches along the radius from the center. We determined to test these rods for permanent set. Four rods were chosen at random and tested in a device constructed to reproduce as nearly as possible the conditions under which the spring operated in the squirrel cage. A hole of the same size as the hole in the spring head flange was bored in a block of iron of the same thickness as the spring head. The drill rod was inserted in this and the nut placed on the end, thus bolting the rod and iron together, the shrouded nut on the rod holding it against the iron. The whole was then placed in a vise with the free end of the drill rod projecting upward. A small aluminum pointer was slipped on the end of the rod and a scale adjusted on an arm in convenient position. We then took bend tests both left and right to ascertain whether we got any permanent set. The data follows:

Distances in Centimeters.

Rod 1.

	Left					Right				
Start	6.9	6.95	7.00	7.07	7.20	7.40	7.35	7.20	7.00	6.65
Max.	8.0	9.00	10.00	11.00	12.50	6.50	5.00	3.50	2.00	1.00
Return	6.95	7.00	7.07	7.20	7.40	7.35	7.20	7.00	6.65	6.43
Set	.05	.05	.07	.13	.20	.05	.15	.20	.35	.22
Total Set					.50					.97

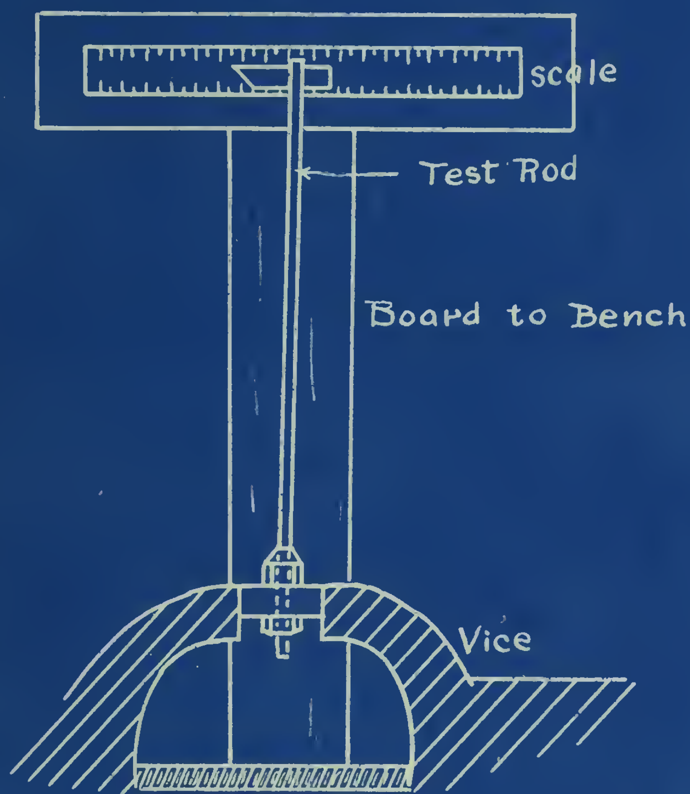


Figure 19

Device For Individual Bend Test of Rods

Rod 2.

	Left					Right				
Start	6.65	6.70	6.76	6.88	7.20	6.84	6.84	6.84	6.80	6.65
Max.	8.50	9.50	10.50	12.00	12.50	6.00	5.00	3.50	2.50	1.00
Return	6.70	6.76	6.88	7.20	7.3	6.84	6.84	6.80	6.65	6.40
Set	.05	.06	.12	.32	.1	00	00	.04	.15	.25
Total Set					.65					.44

Rod 3.

Start	6.64	6.64	6.65	6.70	6.8	7.05	7.05	6.95	6.80	6.6
Max.	8.50	9.50	10.50	11.50	12.50	6.00	5.00	3.50	2.00	1.0
Return	6.64	6.65	6.70	6.8	7.05	7.05	6.95	6.80	6.60	6.35
Set	0	.01	.05	.1	.25	0	.1	.15	.20	.25
Total Set					.41					.70

Rod 4.

Start	7.2	7.2	7.21	7.22	7.6	7.52	7.4	7.00	6.85
Max.	8.5	9.5	11.00	13.50	6.0	5.0	3.0	2.00	1.00
Return	7.2	7.21	7.22	7.6	7.52	7.4	7.0	6.85	6.52
Set	0	.01	.01	.38	.08	.12	.4	.15	.33
Total Set				.40					1.08

It will be seen from these data that set is very noticable. We must either temper the drill rods or resort to some other means.

We had in the shop some vanadium steel spring tempered rods of the desired size. These we subjected to the same test as we did the drill rods with results shown as follows:-

Distances in Centimeters.

Rod 1.

	Right					Left				
Start	12.15	12.15	12.15	12.15	12.15	12.15	12.15	12.15	12.15	12.17
Max.	14.0	14.5	15.0	15.5	16.0	13.0	10.0	9.0	8.5	7.0
Return	12.15	12.15	12.15	12.15	12.15	12.15	12.15	12.15	12.17	12.20
Set	0	0	0	0	0	0	0	0	.02	.03
Total Set					0					.05

Rod 2.

Start	11.25	11.25	11.25	11.25	11.25	11.25	11.25	11.25	11.25	11.25
Max.	12.5	13.0	13.5	14.0	15.0	10.0	9.0	8.5	8.0	7.0
Return	11.25	11.25	11.25	11.25	11.25	11.25	11.25	11.25	11.25	11.20
Set	0	0	0	0	0	0	0	0	0	.05
Total Set					0					.05

Rod 3.

	Right					Left			
Start	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.15	10.10
Max.	11.0	12.0	12.5	13.0	13.75	9.0	8.0	7.0	6.5
Return	10.2	10.2	10.2	10.2	10.0	10.2	10.15	10.10	10.10
Set	0	0	0	0	0	0	.05	.05	0
Total Set					0				.1

Rod 4.

Start	10.85	10.85	10.85	10.85	10.85	10.85	10.85	10.85	10.85
Max.	12.0	13.0	13.0	13.5	14.0	10.0	9.0	8.0	7.5
Return	10.85	10.85	10.85	10.85	10.85	10.85	10.85	10.85	10.85
Set	0	0	0	0	0	0	0	0	0
Total Set					0				0

The maximum bend the rods would ever be subjected to would be about 3 1/2 cm. at their extreme end. This would represent an angle of twist of 20°. As can be seen the results obtained here were very encouraging. We therefore inserted all vanadium spring steel rods in the cage and ran a prony brake test to see if the spring as a whole took any permanent set.

2. <u>Prony</u> <u>Brake</u> <u>Test</u>.——The method of making a prony brake test is well known. The power transmitted is absorbed by the friction of a rope held by suitable fastening so as to measure torque on a scale, or by blocks of wood bolted to a pulley and having a lever arm acting on a scale platform. We used the rope brake. We find that no set is present. This is shown as follows:- We set our angle at random and read E_r. We again set on the other side of the zero position to give the same reading of E_r. Half way between the angle readings noted above should be the zero position. We set at this calculated position and find in every case that it is the true zero and that this zero holds throughout the application of load at the same speed. It will be noted that following the test the same settings were made and the zero point remained unchanged. In view of the fact that the working of the machine depended upon this point, several tests of this kind

[illegible]

were made, data of which follows.

Angle Adjustment Before Test.
$\theta = 9.0 - E_r = 2.1$
$\theta = -.1 - E_r = 2.1$
$\theta = 4.5 - E_r = .2$

I_f	Speed E_s	E_r	Gross Scale Weight lbs.
3	53	1.9	50
3	53	1.9	50
3	53.7	2.74	60
3	53.7	2.76	60
3	53	3.5	70
3	53	3.5	70
3	53.5	4.3	80
3	53.5	4.31	80
3	53.8	5.1	90
3	53.8	5.15	90
3	53.1	5.85	100
3	53.1	5.86	100

Angle Adjustment After Test.
$\theta = 9.0 - E_r = 2.1$
$\theta = -.1 - E_r = 2.1$
$\theta = 4.5 - E_r = .2$

Note: .2 is approximately as near as we can read the balance of the voltages, so this corresponds to zero.

Angle Adjustment Before Test.
$\theta = 0^\circ - E_r = 1.5$
$\theta = 6^\circ - E_r = 1.5$
$\theta = 3^\circ - E_r = .17$

I_f	Speed E_s	E_r	Gross Scale Weight Lbs.
3	60	3.	50
3	60	3.01	50
3	60.5	3.91	60
3	60.6	3.91	60
3	60.	4.74	70
3	60.	4.73	70
3	60.1	5.63	80
3	60.1	5.62	80
3	59.8	6.45	90
3	59.9	6.40	90
3	60.1	7.32	100
3	60.1	7.32	100

Angle Adjustment After Test.
$\theta = 0^\circ - E_r = 1.5$
$\theta = 6^\circ - E_r = 1.5$
$\theta = 3^\circ - E_r = .17$

Angle Adjustment Before Test.

$\theta = 0^\circ - E_r = 2.35$

$\theta = 6.50^\circ - E_r = 2.35$

$\theta = 3.25^\circ - E_r = .15$

I_f	Speed E_s	E_r	Gross Scale Weight Lbs.
3	75.4	3.5	50
3	75.5	3.5	50
3	75.0	4.57	60
3	75.0	4.58	60
3	75.2	5.68	70
3	75.2	5.70	70
3	75.2	6.79	80
3	75.5	6.83	80
3	75.0	7.74	90
3	75.0	7.80	90

Angle Adjustment After Test.

$\theta = 0^\circ - E_r = 2.35$

$\theta = 6.50^\circ - E_r = 2.35$

$\theta = 3.25^\circ - E_r = .15$

Angle Adjustment Before Test.

$\theta = 0^\circ - E_r = 2.35$

$\theta = 6.6^\circ - E_r = 2.35$

$\theta = 3.3^\circ - E_r = .15$

I_f	Speed E_s	E_r	Gross Scale Weight Lbs.
3	91.	4.25	50
3	90.8	4.22	50
3	90.8	5.62	60
3	90.8	5.55	60
3	91.	6.90	70
3	91.	6.90	70
3	91.2	8.20	80
3	90.5	8.15	80
3	90.	9.25	90
3	90.	9.25	90

Angle Adjustment After Test.

$\theta = 0^\circ - E_r = 2.35$

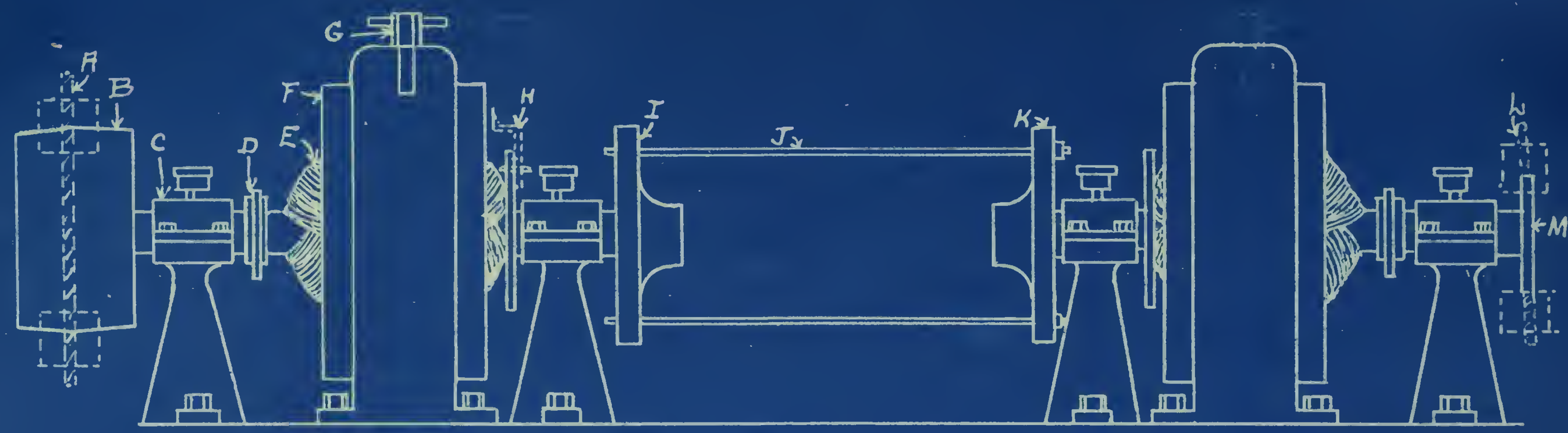
$\theta = 6.6^\circ - E_r = 2.35$

$\theta = 3.3^\circ - E_r = .15$

3. Static Torque Test.-- This was to ascertain if the spring deflected at different torques according to a straight line law as previously explained. In order to do this a lever arm L was securely bolted to one flange. This arm extended onto a scale platform. A lever A was also securely fastened to the pulley on the free end of the machine. A small pointer H was mounted on the free spring flange. Now when lever A was pulled the springs were bent. The pointer indicated the angle, and the torque was indicated by an arm L which extended over and pressed down upon the scale. The pointer is shown attached in Fig. 20.

The result of this test is shown in Fig. 21. It shows that this design obeys a straight line law.

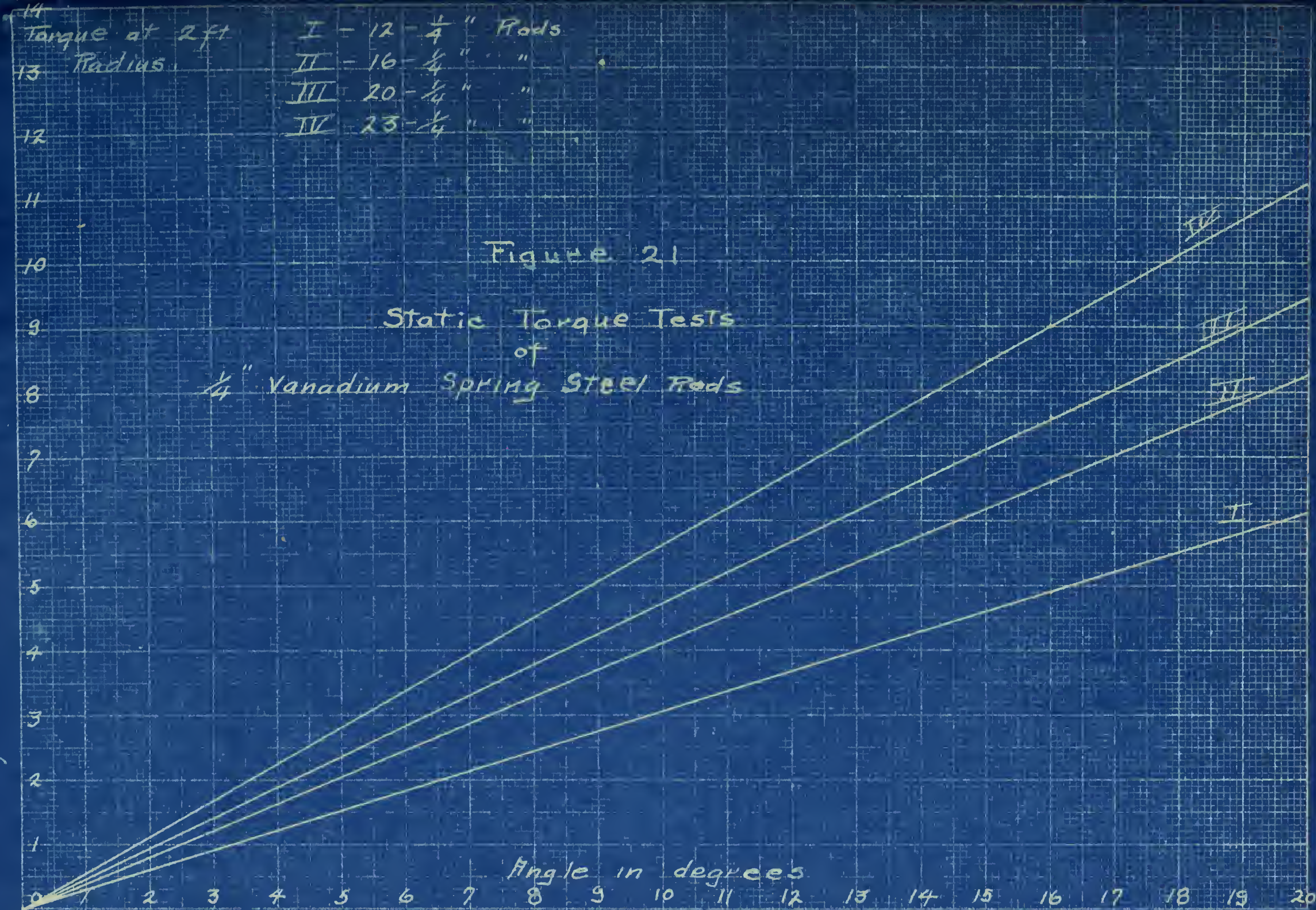
Figure 20



Diagrammatic Sketch of Machine

A = Brake
B = Pulley
C = Bearing
D = Slip Ring
E = Distributed Pole
F = Armature
G = Set Screw to Adjust for Zero
H = Pointer (used only temporarily)

I = Spring Tail
J = Spring Rod
K = Spring Head
L = Fixed Arm (used only temporarily)
M = Coupling.


Torque at 2 ft Radius
I - 12 - 1/4" Rods
II - 16 - 1/4" "
III 20 - 1/4" "
IV 23 - 1/4" "
Figure 21
Static Torque Tests of 1/4" Vanadium Spring Steel Rods
Angle in degrees
I
II
III
IV
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20

B. Effects of Residual Magnetism.

In order to determine whether residual magnetism was of great enough amount to have any effect, we took the curves shown in Fig. 23. We ran the field current up to a high value noting the voltage at the same time. We then lowered the field current. (Speed was kept constant.) We did this thing a number of times and each time the curves came together at $I_f = 3$ amperes, and show practically no residual magnetism. The fact that the curves do not coincide along their entire length may be explained as follows: Fig. 22 shows the saturation curves of the two machines. They differ slightly, but at the value of exciting current we use, that is, $I_f = 3$ amperes, they cross.

C. Effects of Impedence on Error of Resultant in New Design.

The reactance of the new armature winding of each machine was measured by the method of impedence drop. The results are as follows:

South Meter, East Armature, Poles in Position

Impedence.

Freq.	E	I	Z	Average.
60	6	1.59	3.77	
60	7	1.90	3.69	
60	8.2	2.10	3.90	
60	9.2	2.50	3.61	3.74

D. C. Resistance.

E	I	r	Average
3.4	2.12	1.6	
4.6	2.9	1.59	1.595

From which $x = 3.365$ ohms
$L = .0089$ henries

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[illegible]

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[illegible]	[illegible]	[illegible]

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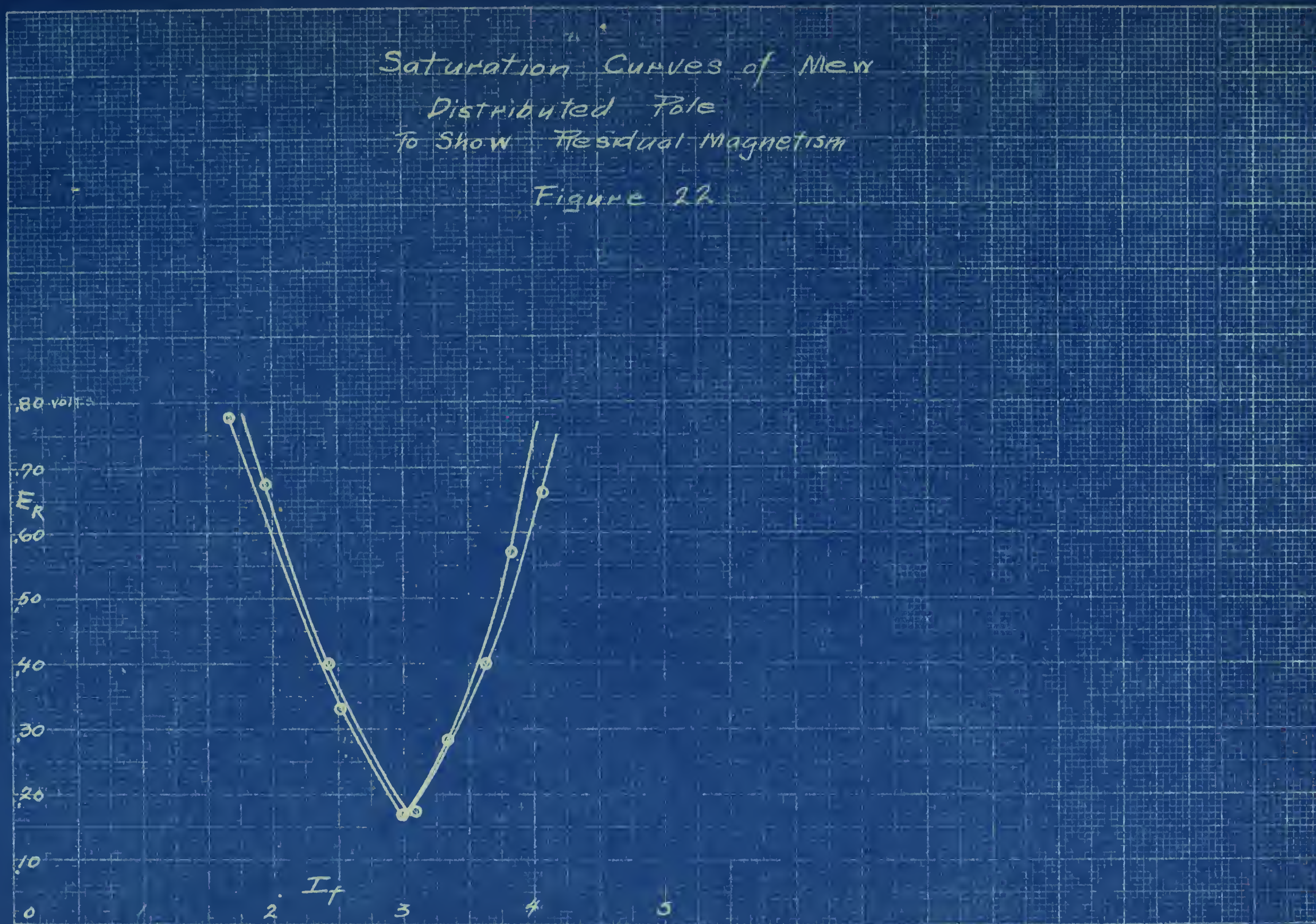

Saturation Curves of New
Distributed Pole
To Show Residual Magnetism

Figure 22

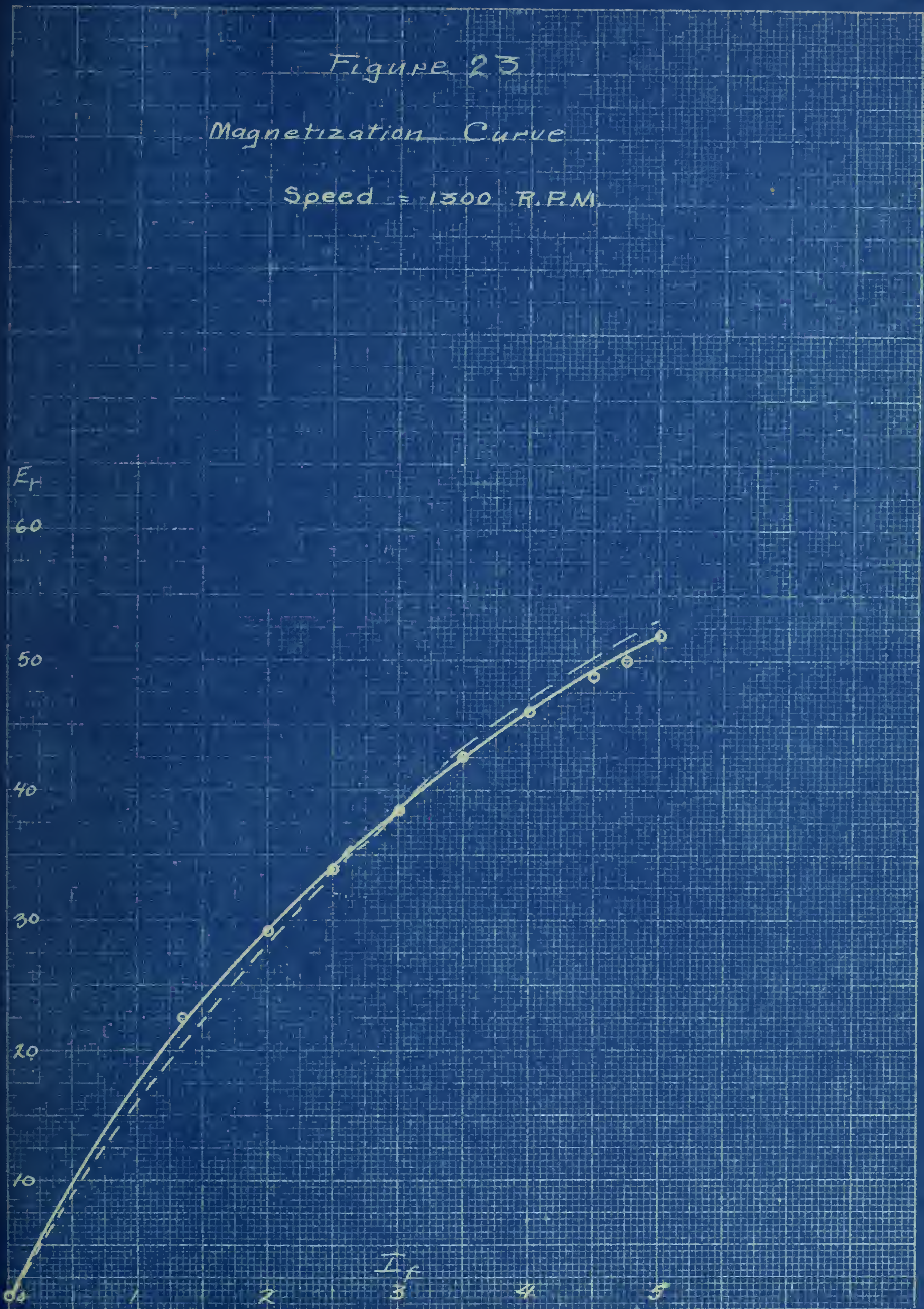
Figure 23
Magnetization Curve
Speed = 1300 R.P.M.
E_r
60
50
40
30
20
10
0
1
2
3
4
5
I_f

South Meter, West Armature, Poles in Position.

Impedence.

Freq.	E	I	Z	Average.
60	6.5	1.59	4.09	
60	7.6	1.90	4.00	
60	8.8	2.10	4.18	
60	10.9	2.50	4.36	
60	13.1	2.95	4.42	4.21

D. C. Resistance.

E	I	r	Average.
3.4	2.08	1.64	
4.9	2.97	1.64	1.64

From which x = 3.88 ohms
L = .0103 henries.

North Machine, East Armature, Poles Removed.

Impedence.

Freq.	E	I	Z	Average.
60	3.5	1.64	2.135	
60	4.15	2.00	2.075	
60	5.30	2.52	2.10	
60	6.22	3.0	2.073	2.1915

D. C. Resistance.

E	I	r	Average.
2.65	1.64	1.615	
3.2	2.00	1.60	
4.1	2.52	1.625	
4.8	3.0	1.60	1.61

From which x = 1.5 ohms, L = .00397 henries.

North Machine, West Armature, Poles Removed.

Impedence.

Freq.	E	I	Z	Average.
60	3.48	1.64	2.12	
60	4.25	2.04	2.08	
60	5.22	2.55	2.05	
60	6.30	3.05	2.06	2.08

D. C. Resistance.

E	I	r	Average.
2.6	1.65	1.58	
3.15	2.01	1.57	
3.95	2.51	1.57	
4.70	3.02	1.56	1.57

From which $x = 1.36$ ohms
$L = .0036$ henries.

It will be seen that we now have an altogether different value of impedence to deal with than was present in the old armature which was about 70 ohms each of resistance and reactance. As mentioned in III-A we are now able to use an ordinary commercial voltmeter of a small resistance without causing the instrument reading to differ from the true resultant by more than one per cent at the highest speed. We show this as follows:

Using an armature winding of 125 turns wound on a skew,

$r_1 = r_2 = 1.7$ ohms; $x_1 = x_2 = 1.9$ ohms at 30 cycles and 1800 r.p.m. $I_f = 3$ amp. Distributed pole.

Total $R = 3.4$ ohms

Total $X = 3.8$ ohms

See Fig. 24.

Now if θ be made 7° (not greater)

$$Z = \frac{3.8}{\sin\theta} = \frac{3.8}{.1218} = 31.2 \text{ ohms}$$

Then $r + 3.4 = 31.2 \cos\theta = 31.2 \times .992 = 31.0$

Or $r = 27.6$ ohms.

This shows that we may use any of the commercial types of voltmeters with perfect safety, all being well above the limiting resistance of 27.6 ohms.

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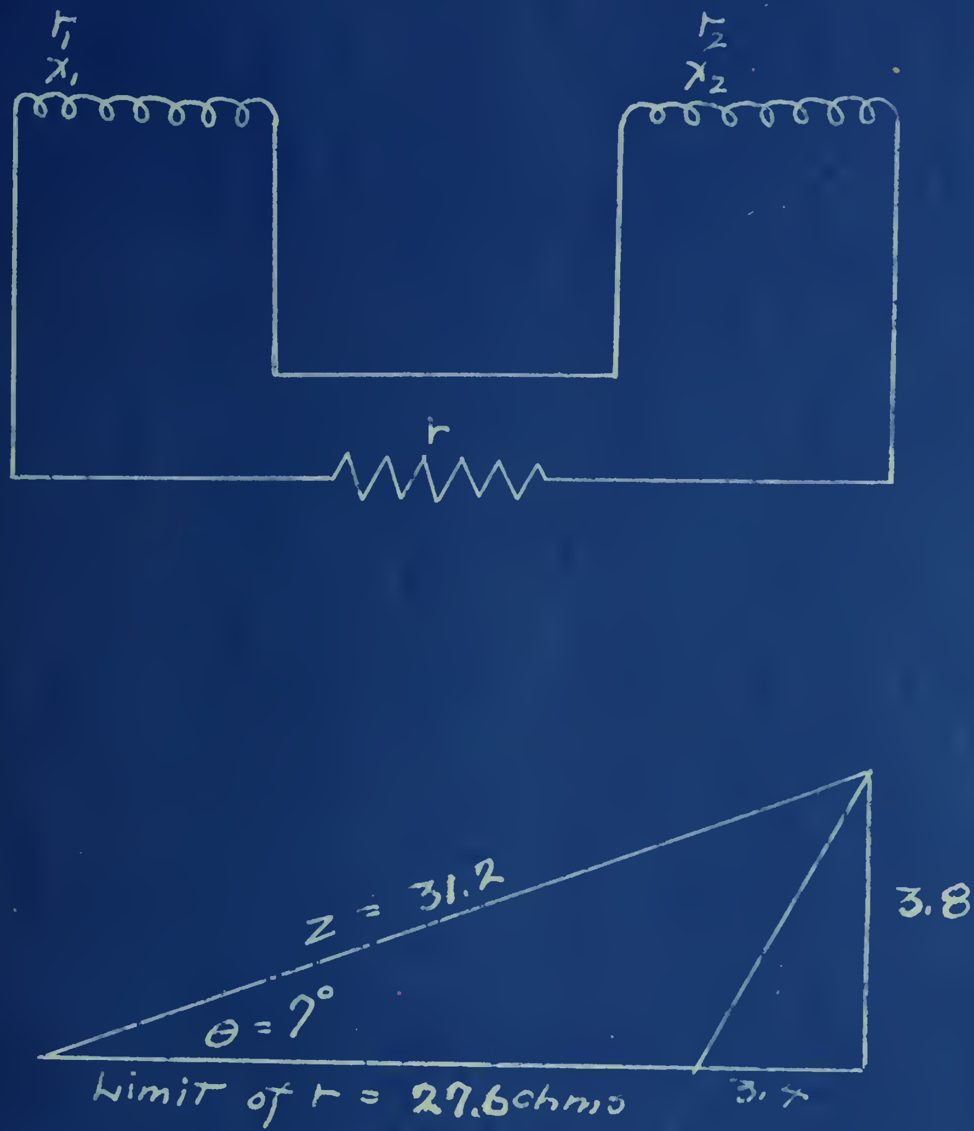

Figure 24

D. Use of Resisance with Voltmeter on the High Scale.

In order that we might use a multiple scale voltmeter for measuring, we must insert a multiplying resistance in the circuit. This will be explained as follows:

The conditions in the circuit are:

$$i = \frac{E}{\sqrt{(r + R)^2 + X^2}} \quad \text{where}$$

E = the resultant voltage

i = the current in the circuit

r = the resistance of the instrument

R = the resistance of the armatures.

Then if we use a different scale on the instrument with a corresponding different resistance, the current may be represented by

$$i_2 = \frac{E}{\sqrt{(r_2 + R)^2 + X^2}}$$

Then the ratio of the two currents will be

$$\frac{i_1}{i_2} = \frac{\cancel{E}}{\sqrt{(r + R)^2 + X^2}} \times \frac{\sqrt{(r_2 + R)^2 + X^2}}{\cancel{E}}$$

$$= \text{some given ratio.}$$

In our case, one scale was twice the other or we have

$$\frac{i_1}{i_2} = 2$$

or $$\frac{\sqrt{(r_2 + R)^2 + X^2}}{\sqrt{(r + R)^2 + X^2}} = 2$$

and $$\frac{(r_2 + R)^2 + X^2}{(r + R)^2 + X^2} = 4$$

Simplifying: $$(r_2 + R)^2 + X^2 = 4(r + R)^2 + 4X^2$$

$$(r_2 + R)^2 = 4(r + R)^2 + 3X^2$$

[illegible]
[illegible]

[illegible]

$$[illegible]$$

$$[illegible]$$

$$[illegible]$$

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[illegible]

$$[illegible]$$

$$[illegible]$$

[illegible]
[illegible]

$$r_2 = 2\sqrt{(r + R)^2 + 3X^2} - R$$

Let us, for example, now substitute the values we used. Our instrument had a resistance of 100 ohms on the lower scale, 200 on the upper or higher scale. The resistance of the armatures was 3.4 ohms. The reactance of the armatures was 3.8 ohms, at 1800 r.p.m. Substituting:

$$r_2 = 2\sqrt{(100 + 3.4)^2 + 3(3.8)^2} - R$$

$$r_2 = 207.2 - R$$

$$= 203.8 \text{ ohms.}$$

Now in order to show that the reactance makes very little difference, let $X = 0$.

Then $e = E - iR$

And the equation for current becomes

$$i = \frac{E}{R + r}$$

Or with another resistance

$$i_2 = \frac{E}{R + r_2}$$

And for a double scale reading

$$\frac{i}{i_2} = 2 = \frac{r_2 + R}{r + R}$$

From which

$$r_2 = 2(r + R) - R$$

Substituting actual values we obtain

$$r_2 = 2(100 + 3.4) - R$$

$$= 203.4$$

which value is within a very small per cent of the other. Hence reactance has negligible effect. Since the scale ratio of 2 was used, and the low scale instrument resistance was taken to be 100 ohms, the commercial instrument would have 200 ohms for the high

scale. Hence, we must insert a resistance of 3.4 ohms to obtain the ratio.

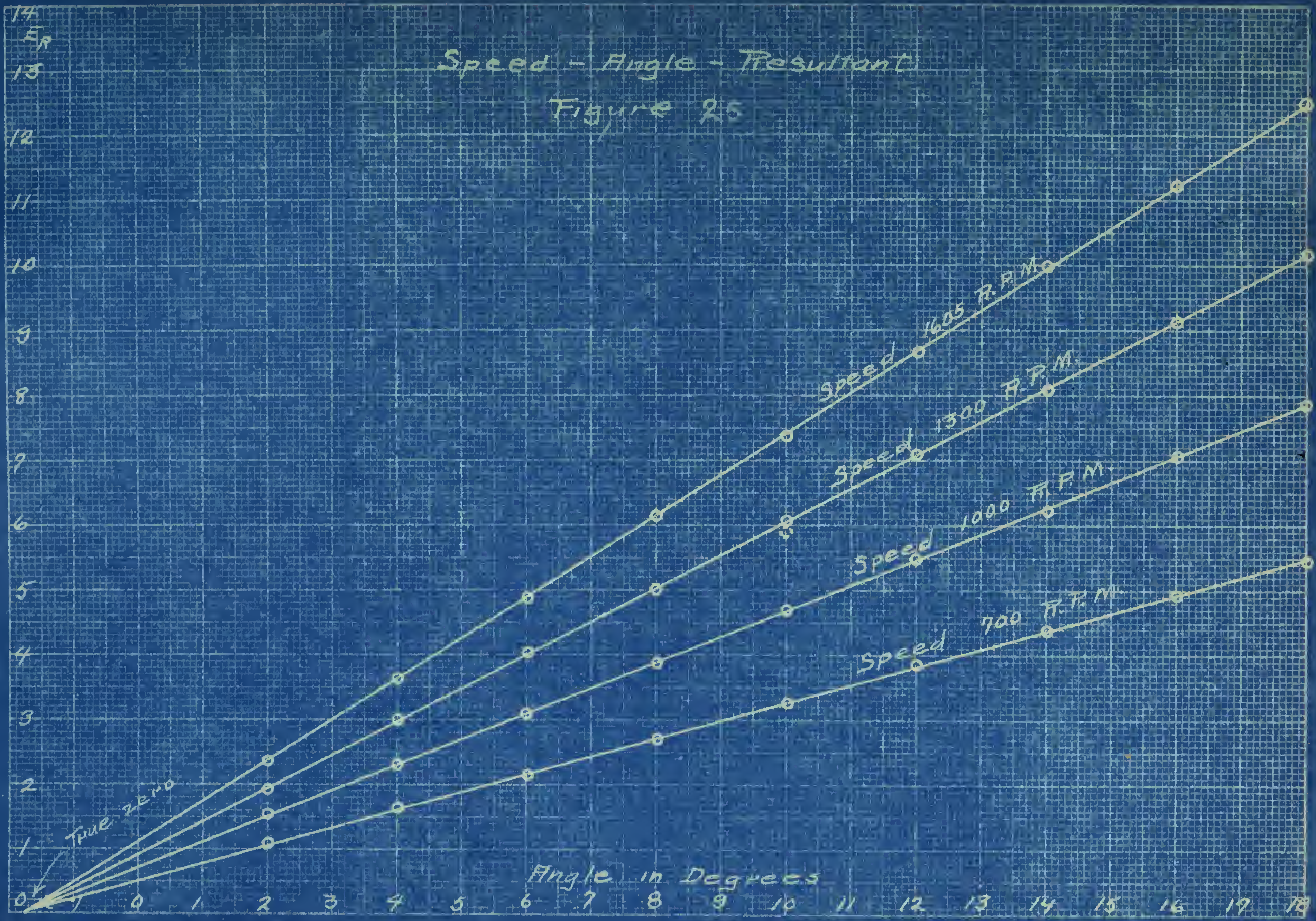
E. Tests of Machine as a Whole.

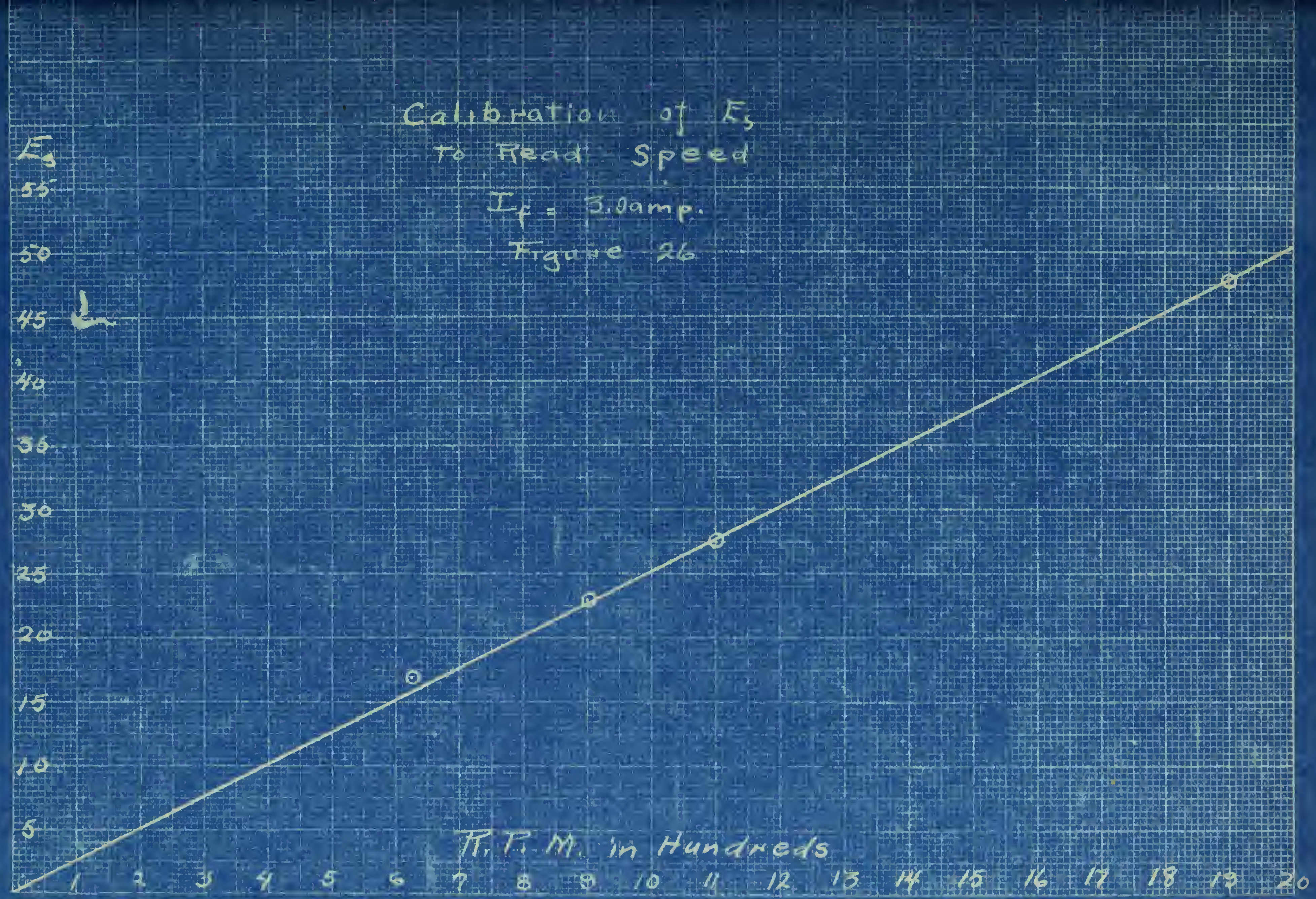
The performance of the machine as a whole is shown by the following curves - Fig. 25, 26, 27, and 28. Here it is seen that

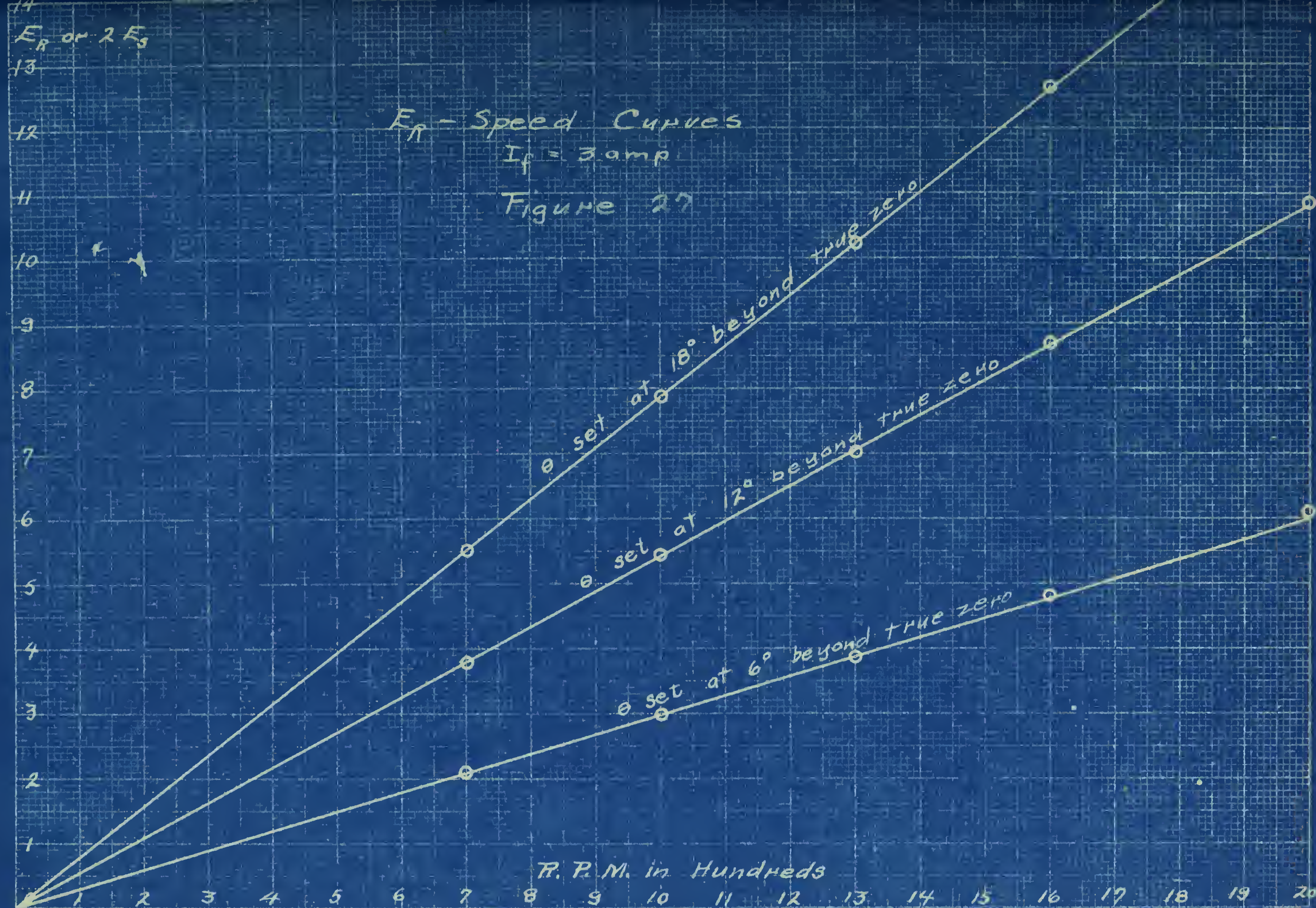
1. The slope of the resultant -- angle line changes directly as the speed.

2. The machine reads horse power directly no matter at what speed providing the zero position is adjusted at each different speed.

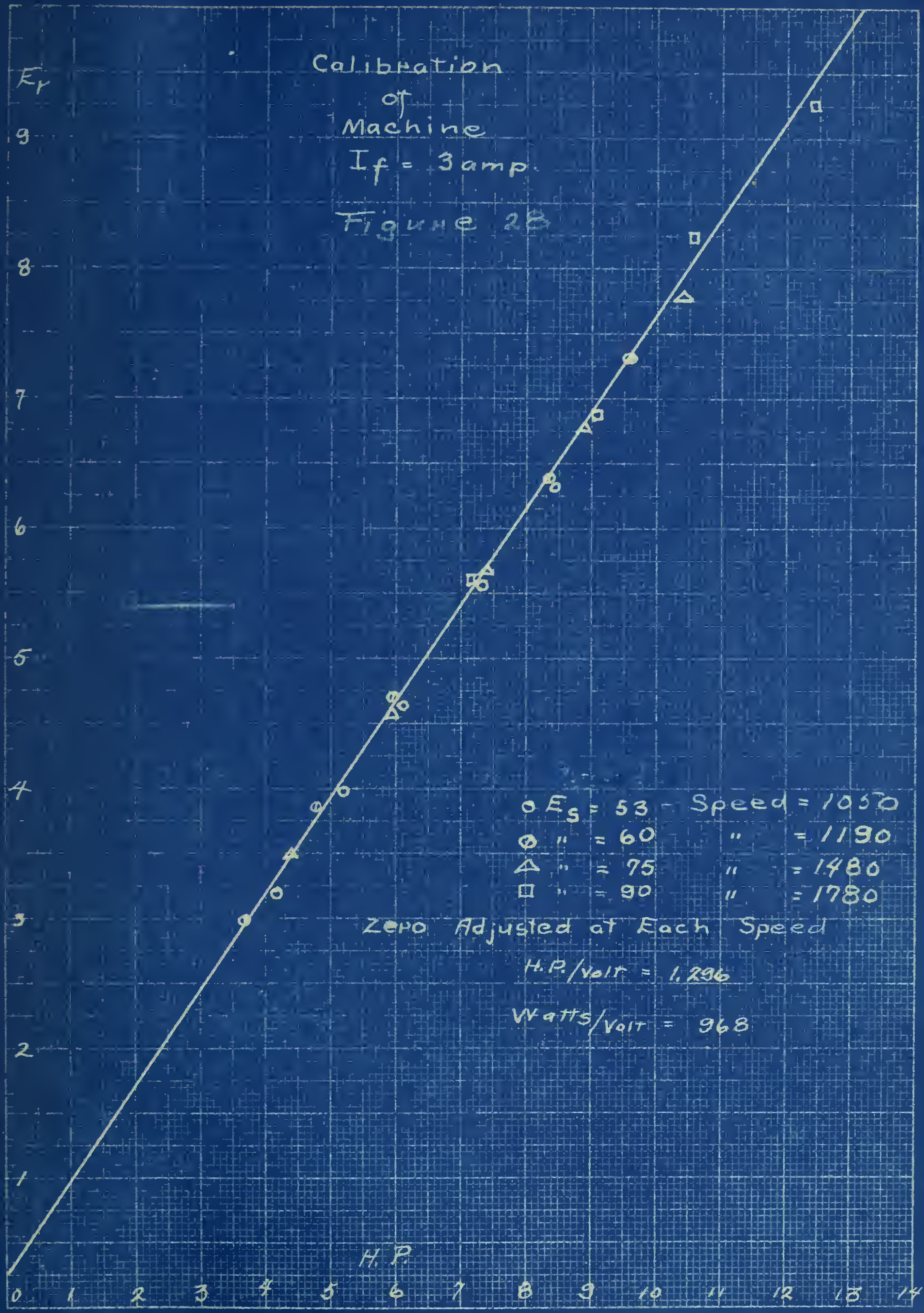
Fig. 29 shows the completed machine.


Speed - Angle - Resultant
Figure 25
E_R
Speed 1605 R.P.M.
Speed 1300 R.P.M.
Speed 1000 R.P.M.
Speed 700 R.P.M.
True zero
Angle in Degrees
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14


Calibration of E_s
to Read Speed
I_f = 3.0 amp.
Figure 26
E_s
55
50
45
40
35
30
25
20
15
10
5
R.P.M. in Hundreds
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20



E_R or $2E_s$
E_R - Speed Curves
I_f = 3 amp
Figure 27
θ set at 18° beyond true zero
θ set at 12° beyond true zero
θ set at 6° beyond true zero
R. P. M. in Hundreds
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
1 2 3 4 5 6 7 8 9 10 11 12 13


Calibration
of
Machine
I_f = 3 amp.
Figure 2B
E_r
H.P.
o E_s = 53 Speed = 1050
⌀ " = 60 " = 1190
△ " = 75 " = 1480
□ " = 90 " = 1780
Zero Adjusted at Each Speed
H.P./Volt = 1.296
Watts/Volt = 968
9
8
7
6
5
4
3
2
1
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14

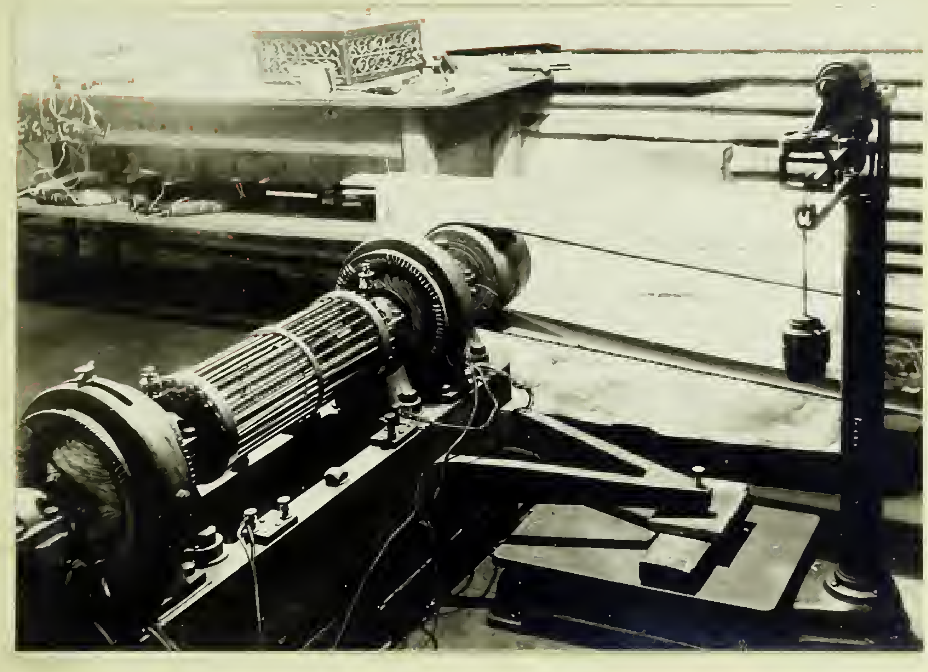


Fig. 29.

APPENDIX A.

One of the uses to which the completed machine may be put is that of belt testing. In this connection there was suggested:

A. The Additional Device to Measure Belt Pull Directly.

In order that belt pull might be measured directly, the device shown in Fig. 30 was made. It consists of a base with an arm mounted on a knife edge. A platform scale is placed under the arm and the pull of belt thus measured directly.

B. The Development of a Testing Laboratory.

A laboratory was necessary to test belts. This we developed. For machines to drive our powermeters we used two Edison bipolar 20 K.W. machines. Our arrangement is as shown in Fig. 31. Both were mounted on ways in order that the proper tension could be given a belt tested. Wood, iron, and paper pulleys were secured in order that the slip of belts on different pulleys could be tested.

C. Couplings.

The question of a suitable coupling to connect the driving machines and the powermeter was brought up. Evidently this coupling must combine the following characteristics:

1. Flexibility over a considerable range.
2. Strength to transmit the required power.
3. Silence.
4. Cheapness and ease of construction.

After investigating a number of possible couplings, the one

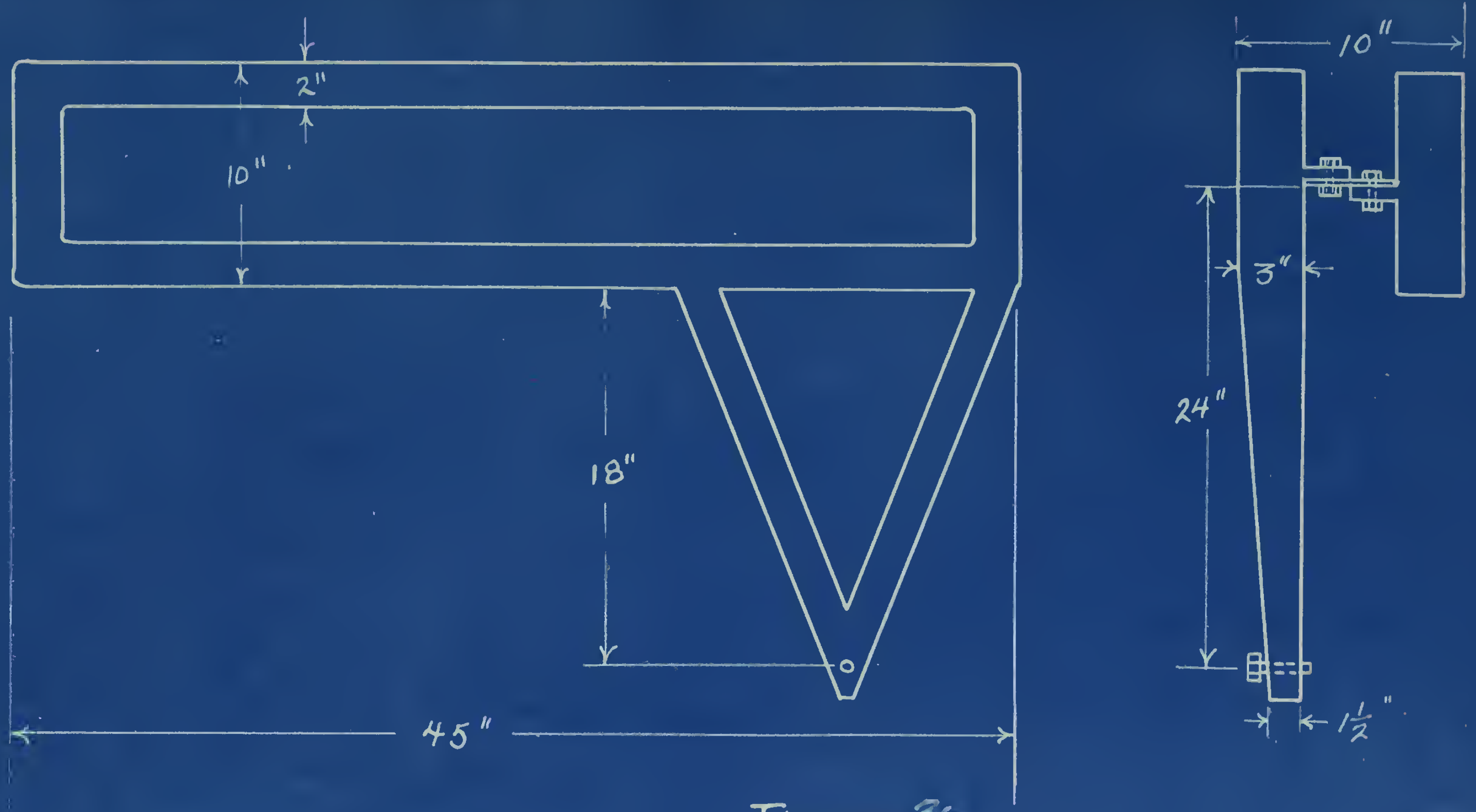


Figure 7c
Additional Device to Measure
Belt Pull Directly

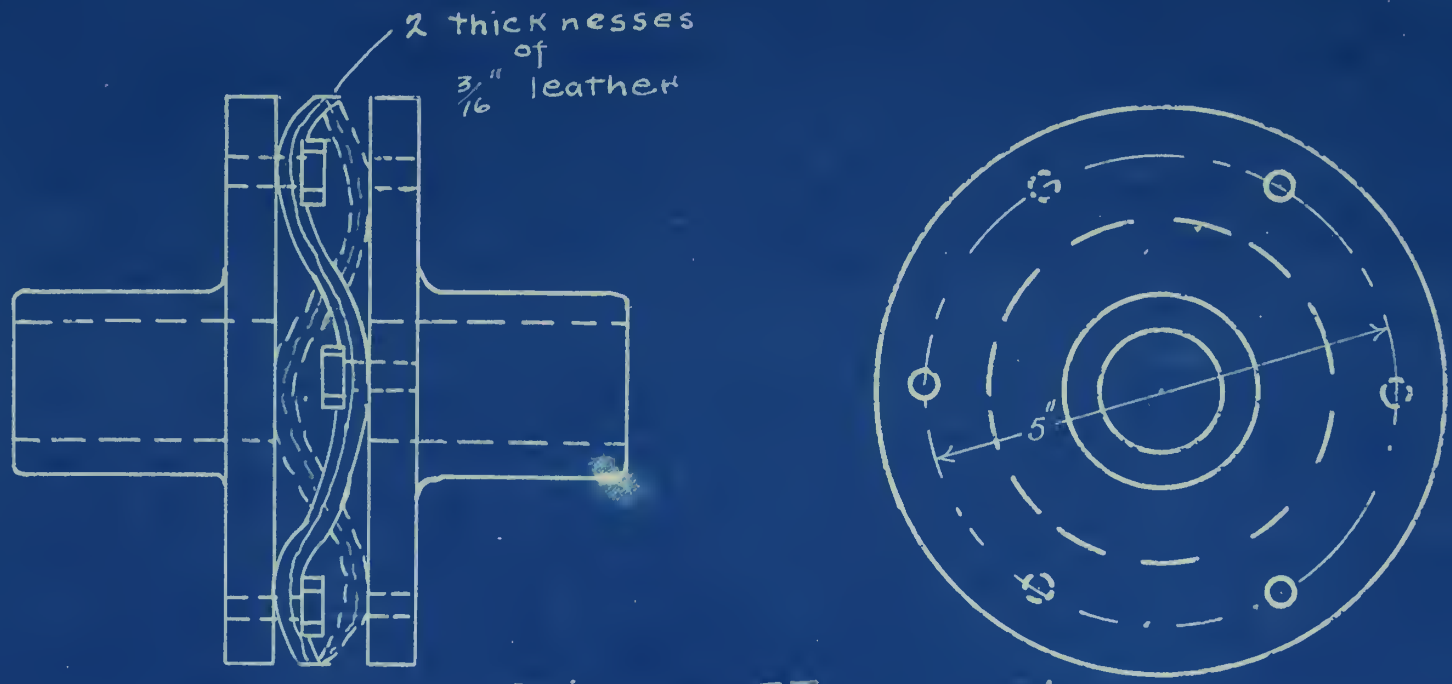


Figure 33

Coupling

shown in Fig. 33 was devised and adopted. It appears to be fairly satisfactory. It consists of two thicknesses of 3/16-inch leather held against flanges by bolts placed alternately on each flange.

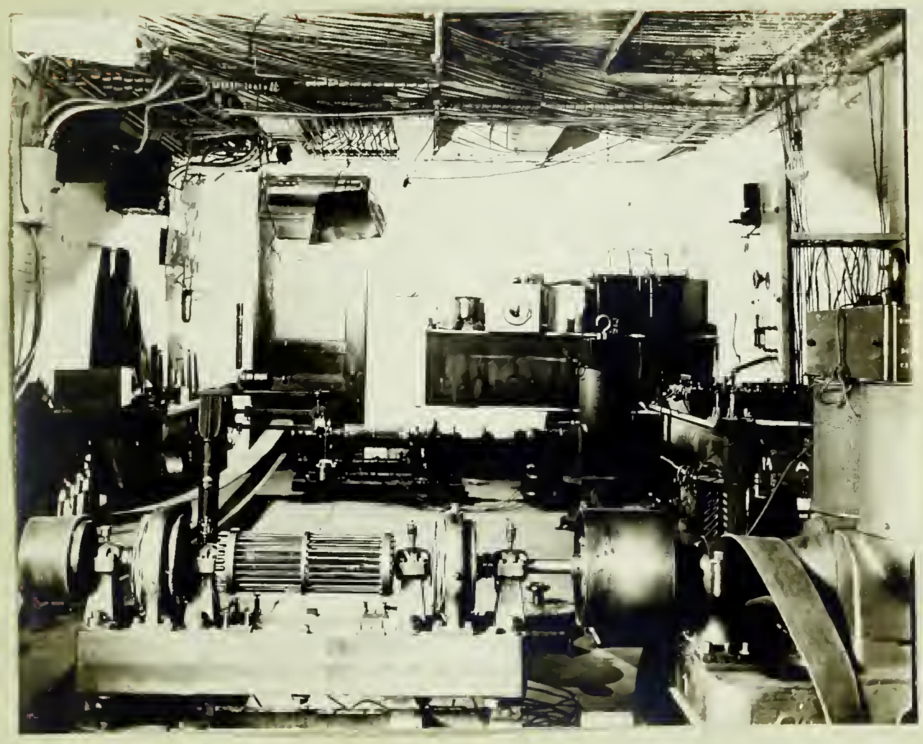
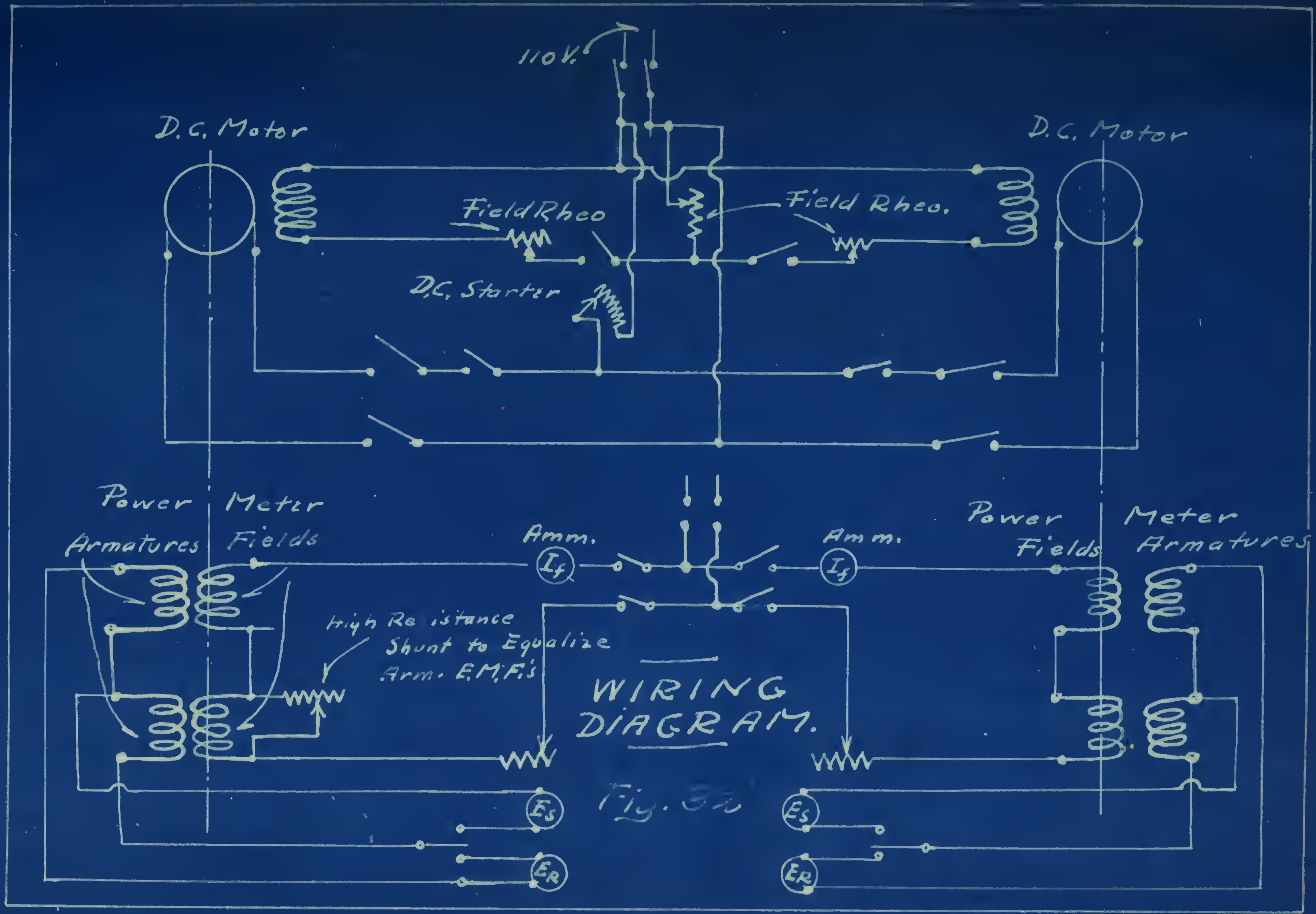


Fig. 31.


110V.
D.C. Motor
D.C. Motor
Field Rheo
Field Rheo.
D.C. Starter
Power
Armatures
Meter
Fields
Power
Fields
Meter
Armatures
Amm.
Amm.
I_f
I_f
High Resistance
Shunt to Equalize
Arm. E.M.F.'s
WIRING
DIAGRAM.
E_S
E_R
E_S
E_R